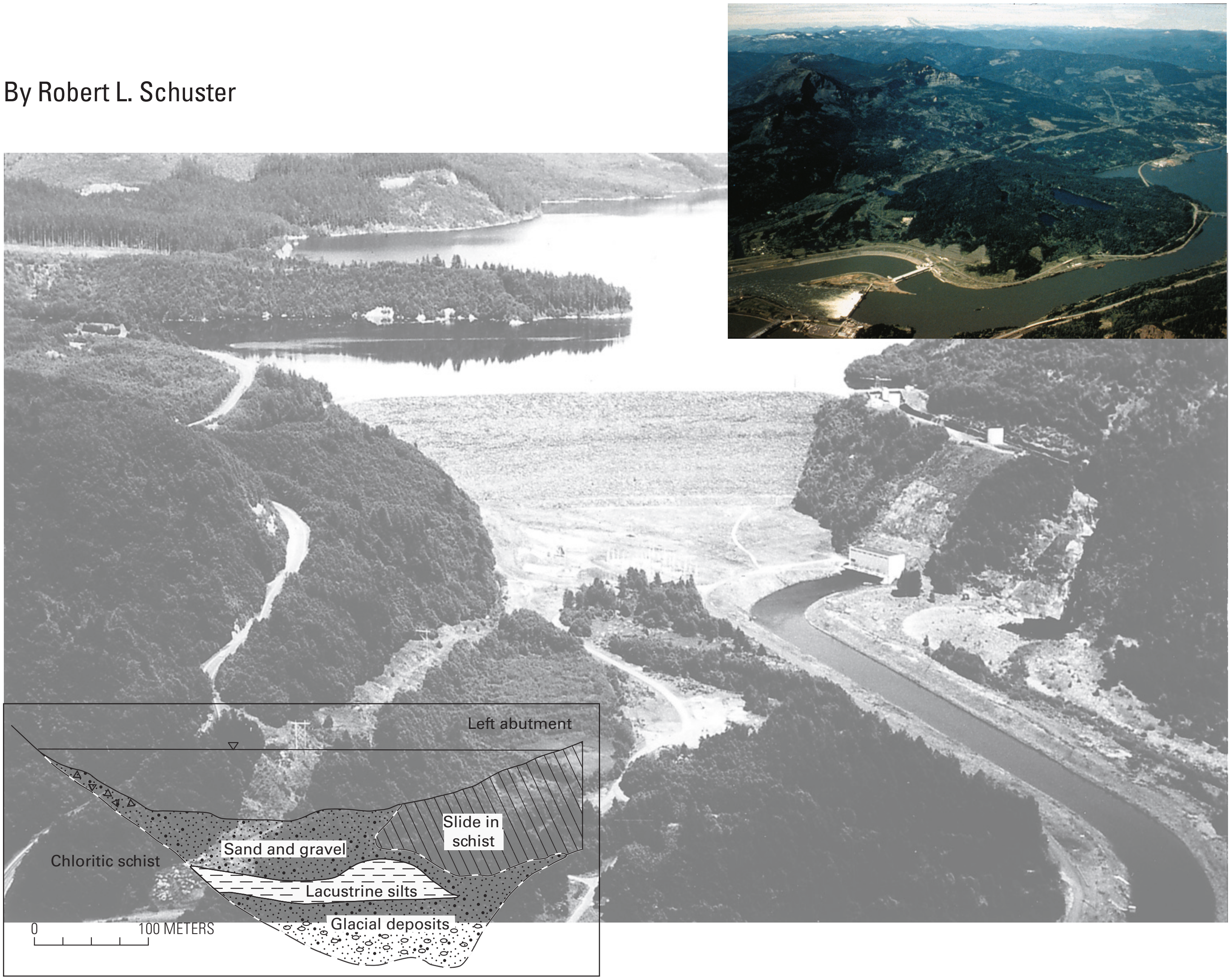
Interaction of Dams and Landslides—Case Studies and Mitigation

By Robert L. Schuster



Professional Paper 1723

U.S. Department of the Interior
U.S. Geological Survey

Cover.—Aerial view of Swift Dam, Lewis River, western Washington State, United States (photograph taken by Lynn Topinka, U.S. Geological Survey).

Top inset.—Bonneville Dam, Columbia River Gorge, Washington and Oregon, United States (photograph taken by Derek Cornforth, Landslide Technology, Portland, Oregon).

Bottom inset.—Cross section through rock slide, Durlassboden Dam, Austria (modified from Záruba and Mencl, 1982).

Interaction of Dams and Landslides—Case Studies and Mitigation

By Robert L. Schuster

Professional Paper 1723

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
Mark D. Myers, Director

U.S. Geological Survey, Reston, Virginia: 2006

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS--the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

Suggested citation:

Schuster, R.L., 2006, Interaction of dams and landslides—Case studies and mitigation: U.S. Geological Survey Professional Paper 1723, 107 p.

Contents

Abstract 1
Introduction 1
  Background 1
  Presentation of Data 2
  Sources of Information 3
  Summary of Data 3
Selected Case Histories of Dams on Landslides (by Landslide Type) 4
  Rock Fall (Including Talus Deposits) 4
  Slides in Competent Rock 6
  Slides in Incompetent rock 13
  Massive Rock Slides and Glide Blocks 13
  Earth and Debris Slides 15
  Rock and Debris Avalanches 16
  Debris, Mud, and Earth Flows 17
  Cambering and Valley Bulging 22
Problems Encountered Due to Interaction Between Dams and Landslides 22
  Abutment and Foundation Instability 22
  Abutment and Foundation Seepage 24
Mitigative Measures 25
  Planning Measures 25
    Avoidance of Landslides 25
      Relocation of Site 25
      Site Abandonment 27
    Redesign of Dams Because of Landslide Problems 27
    Lowering Reservoir Level or Reducing Rate of Filling 28
Physical Measures for Foundation and Abutment Stabilization 28
  Removal of Landslide Deposits 28
    Total Removal of Landslide 28
    Partial Removal of Landslide 28
    Partial Removal of Talus Cover 29
    Partial Removal of Landslide Deposit Following Construction or Postconstruction Slope Failure 29
  Flattening Abutment Slopes 29
  Earthfill or Rockfill Berms Serving as Buttresses 29
  Dam Serving as Buttress 30
  Cutoffs or Keys 30
  Retaining Walls 30
  Piles and Caissons 30
  Anchors 30
  Moving or Reinforcing Spillway 30
  Guniting 31
  Dental Work 31

Physical Measures for Reducing Abutment and Foundation Seepage....31
  Impervious Cutoffs....31
  Impervious Curtains, Membranes, and Blankets....31
  Drainage Systems....32
  Multiple Mitigation Methods....32
  Breaching as a Remedy....32
Summary and Conclusions....33
Acknowledgments....33
References Cited....33
Appendix....51

Figures

1. Original sketch map and cross section showing landslide conditions at Farmers Union (now Rio Grande) Dam, southwestern Colorado, United States....2
2. Photograph of Mammoth Pool Dam, San Joaquin River, California, United States....5
3. Cross section through the narrow gorge in the foundation of Waterbury Dam, Little River, Vermont, United States....5
4. Views before and after construction of Taylor Park Dam, central Colorado, United States....6
5. Gross Dam, Colorado, United States....7
6. Gravity-slip surfaces in granitic foundation rocks at Gross Dam, Colorado Front Range, United States....7
7. Photograph looking upstream at the remains of St. Francis Dam, southern California, United States....8
8. Cross section through the 1928 left-abutment landslide at St. Francis Dam, California, United States....8
9. Cross section through the pre-existing rock slide that forms the left abutment of Beauregard Dam, northwestern Italy....8
10. Simplified cross-valley cross section through Dalešice Dam, Jihlava River, Czech Republic....9
11. Oblique view of Tablachaca Dam, Peru....10
12. Photograph looking upstream at the right-abutment landslide at Tablachaca Dam, Peru....10
13. Map of rock slide at the right abutment of Tablachaca Dam, Peru....10
14. Photograph of Lake Harriet Dam, Cascade Range, Oregon, United States....10
15. Major Holocene landslide deposits in the Columbia River Gorge, Washington and Oregon, United States....11
16. Oblique aerial view of Bonneville Dam in the Columbia River Gorge, Washington and Oregon, United States....12
17. Map of the Cascades landslide complex and its components, United States....12
18. Simplified cross section through the rock slide in schist that forms the right abutment of Durlassboden Dam, Austria....12
19. Photograph of Fruitgrowers Dam, western Colorado, United States....13

20. Locations of 18 dams on landslide bench and slump-block landslides derived from the basalt plateau of the Grand Mesa, western Colorado, United States 14
21. Photograph of Grand Coulee Dam, eastern Washington State, United States....15
22. Cross section through the Parangana Dam site, Victoria, Australia 16
23. Oblique aerial view of Cheakamus Dam, British Columbia, southwestern Canada....17
24. Cross section through the site of Cheakamus Dam, British Columbia, southwestern Canada....17
25. Aerial-oblique view of Mud Mountain Dam, western Washington State, United States 18
26. Cross section through the site of Mud Mountain Dam, Washington State, United States 18
27. Aerial view of Swift Dam, Lewis River, western Washington State, United States 18
28. Geologic map of the area around Swift Dam, Washington State, United States 19
29. Geologic map of the area around Yale Dam and Yale Saddle Dam, Washington State, United States....20
30. Sketch of the earthfill sediment-retention dam on the North Fork Toutle River, southwestern Washington State, United States 21
31. Photograph of Medeo Dam, a debris-flow retention structure on the Malaya Alma-Atinka River, Kazakhstan 21
32. Photograph of construction of a cellular reinforced-concrete debris-retention dam on the Bolshaya Alma-Atinka River, Kazakhstan....21
33. Cross section through B.F. Sisk (San Luis) Dam, California, United States 23
34. Photograph of Cheurfas Dam 23
35. Photograph of Star Mountain Dam, southeast Oregon, United States 24
36. Oblique-aerial view of Ochoco Dam, central Oregon, United States 24
37. Cross section through the site of Howard Hanson Dam, western Washington State, United States....25
38. Photograph of Scott Dam on the Eel River, northern California, United States 26
39. Cross section through a narrowed section of the Romanche River valley, France....27
40. Oblique view of the left end of Mojave River Dam....29
41. Photograph of the remains of Mystic Lake Dam, southwestern Montana, United States 32

Tables

Appendix Table A. Dam characteristics, relation to landslides, mitigative measures, and cited references.....51

Interaction of Dams and Landslides—Case Studies and Mitigation

by Robert L. Schuster

Abstract

In the first half of the 20th century, engineering geology and geotechnical engineering were in their infancy, and dams were often built where landslides provided valley constrictions, often without expert site investigation. Only the most important projects were subjected to careful geologic examination. Thus, dams were often built without complete understanding of the possible geotechnical problems occurring in foundations or abutments. Most of these dams still exist, although many have undergone costly repairs because of stability or leakage problems. Today, however, every effort is made in the selection of damsites, including those sited on landslides, to provide foundations and abutments that are generally impervious and capable of withstanding the stresses imposed by the proposed dam and reservoir, and possible landslides.

By means of a literature search, technical interviews, and field inventory, I have located 254 *large* (at least 10 m high) dams worldwide that directly interact with landslides; that is, they have been built on pre-existing landslides or have been subjected to landslide activity during or after construction. A table (Appendix table A) summarizes dam characteristics, landslide conditions, and remedial measures at each of the dams. Of the 254 dams, 164 are earthfill, 23 are rockfill, and 18 are earthfill-rockfill; these are flexible dam types that generally perform better on the possibly unstable foundations provided by landslides than do more rigid concrete dams.

Any pre-existing landslides that might impinge on the foundation or abutments of a dam should be carefully investigated. If a landslide is recognized in a dam foundation or abutment, the landslide deposits commonly are avoided in siting the dam or are removed during stripping of the dam foundation and abutment contacts. Contrarily, it has often been found to be technically feasible and economically desirable to site and construct dams on known landslides or on the remnants of these features. In these cases, proven preventive and remedial measures have been used to ensure the stability of the foundations and abutments, and to reduce seepage to acceptable levels.

Introduction

This paper presents case histories of dams that have interacted with landslides in abutments and/or foundations. It uses these case histories to discuss problems caused by different types of landslides and mitigative measures used to alleviate these problems. Note that interactions between reservoirs and landslides are beyond the scope of this paper. Thus, well-known cases of reservoir-induced landslides such as those at Vaiont Dam and Grand Coulee Dam's Lake Roosevelt are not included.

Background

> "Many major slides have in the past blocked up river valleys, the resulting constrictions giving dam sites which appear at first sight to be admirable. In view of the of the nature of the material in slides, and its unconsolidated and often disturbed conditions, sites of this kind may often prove to be very far from ideal. Dams have, however, been successfully founded at such sites" (Legget, 1939, p. 225–226).

> "No structure grips the ground so closely as a dam. It holds on at its base and at its flanks***. In other words, a dam is made up of two parts: the artificial dam, man-made, and the natural dam, which continues it, surrounds it, and on which it is founded. The more important of the two is the latter which is unnoticed" (Martin, 1974, translated from Coyne, 1939).

From Coyne's statement it can be further inferred that any movement, or potential movement, of the foundation or an abutment[1] is critical to the stability and effectiveness of the dam itself. Thus, the possibility of gravitational

---

[1] I will use dam "foundation" as being the rock/soil in direct contact with the base of the dam, and dam "abutments" to be the parts of the valley side slope that are in direct contact with the ends of the dam. Together, the foundation and abutments form the "footprint" of the dam.

movement (landslide[2] activity) in the foundation or an abutment of a dam is of critical importance. Because many (if not most) such movements are reactivations of all or parts of pre-existing landslides, it is extremely important to identify these morphological elements and to realize their possible effects on the dams involved. As noted by Weaver (1989), "Landslides, if recognized prior to construction, presumably are avoided or are removed during stripping of the dam foundation. However, landslides of significant size sometimes occur during the course of stripping operations for a dam on weak rock foundations, and must be left in place."

In the early part of the 20th century, a few experts recognized and presented the problems posed by pre-existing landslides in dam foundations or abutments (see for example, Clarke, 1904; Lapworth, 1911; Atwood, 1918, (his fig. 1); Willis, 1928; Bromehead, 1936; and Legget, 1939). However, in spite of this technical expertise and warning, many, if not most, dams were built without expert examination of damsites; only the most important projects were subjected to careful geologic studies. Thus, dams were often built without complete understanding of the possible geotechnical problems inherent in their abutments or foundations. Today, however, every effort is usually made to select a damsite in which the abutments and foundation are relatively impervious and capable of withstanding the stresses imposed by the proposed dam and reservoir under all probable loading conditions. Thus, permeability and stability of dam abutments and foundations must be considered during site selection, site preparation, construction, and operation of dam structures (Záruba, 1979; Weaver, 1989).

Many post-World War II geologists and engineers have discussed in depth the importance of understanding the existence of landslides at damsites. Among the most noteworthy works have been those of Burwell and Moneymaker (1950), Gignoux and Barbier (1955), Richey (1959, 1964), Walters (1971), Desio (1973), Barbier (1974), Martin (1974), Anderson and Trigg (1976), Záruba and Mencl (1976, 1982), Mencl (1977), Záruba (1979), Hobst and Zajíc (1983), Legget and Karrow (1983), Legget and Hatheway (1988), Galster (1989a,b), Fell and others (1992), Skempas and Chandler (1993), Tolmachev (1994), and Riemer (1995).

It has often been found to be technically feasible and economically desirable to site and construct dams on known landslides or on their partial remnants after most of the material has been stripped from the site. The stability of the landslide or its remnant can be enhanced by the buttressing effect of the dam itself, which can be augmented by berms acting as buttresses, by anchors, or by retaining structures. In addition, problems caused by seepage through the landslide materials usually can be remedied by means of surface or subsurface drains, grout curtains, impervious membranes, or other preventive or remedial measures.

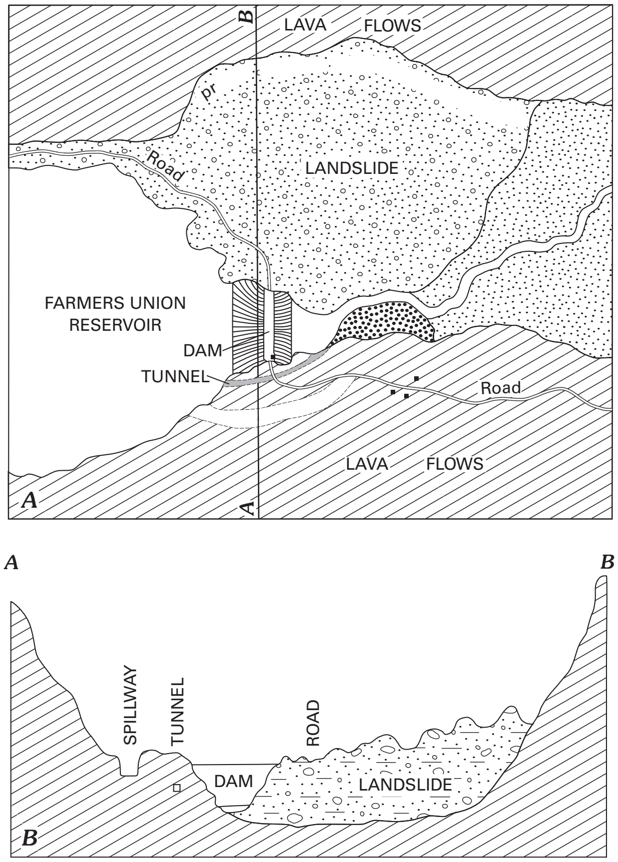


Figure 1. Original sketch map (*A*) and cross section (*B*) along the line *A–B*, showing landslide conditions at Farmers Union (now Rio Grande) Dam, southwestern Colorado, United States (Atwood, 1918, p. 19).

Presentation of Data

Appendix table A presents the cases of 254 large[3] dams that were identified in this worldwide survey of dams built on (1) pre-existing landslides, (2) remnants of partly excavated landslides, and (3) construction-caused or post-construction landslides. It includes only cases in which part or all of the landslide was left in place as part of the foundation or an abutment. The table includes data for a few dams that no longer exist. Each case includes the location, dam and stream names, dam type and purpose, year of dam completion and owner, dam and reservoir dimensions, landslide type and position, comments regarding the landslide and remedial measures, and

---

[2] "Landslide" will include all types of gravitational mass movements, such as falls, slides, avalanches, and flows, according to the landslide classifications of Varnes (1978) and Cruden and Varnes (1996).

[3] For cases in which "the dam had specially difficult foundation conditions," the International Commission on Large Dams (ICOLD) defines a "large" dam as one that is at least 10 m high (International Commission on Large Dams, 1977). Because most dams constructed on landslides fit this specification, I will use 10 m as the minimum height for "large" dams. All dams in Appendix table A are 10 m high or higher, and thus all are "large" dams.

references and other information sources. The purpose of this tabulation is to provide observations and conclusions to aid in future dam-siting decisions.

Some, but not all, of the dams in Appendix table A are also discussed as examples of the basic types of landslides on which dams have been built, as examples of the common problems encountered from interaction of dams and landslides, or as examples of the types of mitigation measures that have been used to solve or reduce problems related to dam and landslide interaction.

Sources of Information

The data presented in Appendix table A have been obtained from the following sources:

- Technical papers, reports, and textbooks appearing in the international geological, geotechnical, and dam-engineering literature
- Government dam-building agencies and consulting companies, mostly in North America
- Geotechnical consultants and colleagues with experience on dams and landslides, mostly in the United States
- Local, State, and Federal dam-safety agencies in the United States
- Personal experience of the author, including visits to nearly all of the U.S. dams listed, as well as several of the foreign dams

Information on dams located outside the United States has been obtained mainly from a detailed search of the international landslide and dam literature. Especially valuable were proceedings of congresses and specialty conferences of the International Commission on Large Dams (ICOLD), the International Association for Engineering Geology and the Environment (IAEG), the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE, formerly known as the International Society for Soil Mechanics and Foundation Engineering), the American Society of Civil Engineers (ASCE), the Association of Engineering Geologists (AEG), and other sources. Also perused were professional journals, such as *Geotechnique, The Quarterly Journal of Engineering Geology,* the *Journal of Geotechnical Engineering, Environmental and Engineering Geoscience,* and *Engineering Geology*. United States proceedings included those of the annual meetings of the U.S. Society on Dams (USSD, formerly known as the U.S. Committee on Large Dams) and the Association of State Dam Safety Officials (United States). Physical data on dams in the United States were obtained from the CD-ROM, *National Inventory of Dams 1996* (Federal Emergency Management Agency, 1996), which includes 76,000 U.S. entries. Landslide information on U.S. dams came partly from published technical papers, partly from the files of Federal dam agencies and State dam-safety organizations, and partly from interviews with professional colleagues in government agencies, universities, and consulting companies. In addition, the author visited nearly all of the U.S. dams entered in the table, as well as several foreign dams, often in the company of local dam officials and personnel. The source(s) of information for each dam is indicated in the last column of Appendix table A.

Summary of Data

Of the 254 dams in the study, 153 are located in the United States; 142 of these are in the conterminous Western States (including, or west of, the Rocky Mountains). The State of Colorado leads the list with 56 dams on landslides (Schuster, 2003), followed by California with 21, Oregon with 18, Utah with 16, and Washington with 14. For the rest of the world, Italy leads with 11 dams, followed by Australia with 7, India, Japan, and the United Kingdom with 6 each, and the Czech Republic and Spain with 5 each. This seeming bias in gathering of data for the Western United States (as compared to that for the rest of the world) probably occurs because of (1) the very large number of dams that have been built in the Western United States, (2) the great number of landslides in the mountains of the Western United States, and (3) the fact that I have closer technical and professional contacts in the Western United States than elsewhere in the world—contacts who have been willing to supply research data to this study. In addition, in the United States, many data were obtained as public information from State dam-safety agencies, an opportunity that did not present itself for other countries. Instead, almost all non-United States case histories were obtained from published papers in technical journals and proceedings. This latter fact also resulted in a preponderance of big dams (as compared to fairly small dams) for foreign countries because incidents involving smaller dams were not as apt to be reported in technical publications. Notable was the lack of available data from the republics of the former U.S.S.R.

Of the 254 cases in Appendix table A, 165 are earthfill, 23 are rockfill, 19 are earthfill and rockfill, 24 are concrete gravity, 13 are concrete arch, 7 are concrete arch-gravity, 2 are masonry/stone, and 1 is unknown. Interestingly, 120 of the 153 U.S. dams are earthfill, probably because of the large number of relatively small (10–50 m high) irrigation dams that have been built in the Western States. The outstanding examples of this earthfill bias are the States of Colorado, where 52 of the 56 dams are earthfill, and Utah, where all 16 dams are earthfill.

With regard to the primary purposes of the 254 dams, 108 are for irrigation, 56 for hydroelectric power, 48 for water supply, 20 for flood control, 12 for recreation, 5 for debris retention, and 5 for tailings or waste disposal. Within the United States, 85 of the dams are for irrigation, 27 for water supply, 14 for flood control, 14 for hydroelectric power, 11 for recreation, 1 for debris retention, and 1 for fly-ash storage.

Colorado, the State with the most dams in this study, includes 42 irrigation dams, 7 recreation dams, 6 water-supply dams, and 1 dam for electric power. Of course, many of the dams also have secondary functions in these same categories.

The structural heights of the 254 dams range from the prescribed minimum of 10 m to a maximum of 170 m. The six highest dams in the study are as follows: Thissavros, Greece (170 m); Upper Gotvand, Iran (170 m); Grand Coulee, United States (168 m); Daniel Palacios, Ecuador (167 m); Thomson, Australia (166 m); and Trinity, United States (164 m). The worldwide distribution of dams by height is as follows: 153 are 10–50 m high, 62 are 51–100 m high, 29 are 101–150 m high, 9 are 151–170 m high, and 1 dam had no height information. This distribution is to be expected because many more dams exist in the lower part of this range than in the upper part. Also, it is to be expected that smaller dams commonly have not been as carefully sited as the larger dams and, consequently, are more apt to be sited on landslides. The large number of relatively small (10–50 m high) dams on landslides worldwide, however, is more specifically a result of the fact that 115 of the 153 U.S. dams in Appendix table A fall in this category.

It is not easy to categorize the 254 tabulated dams by landslide type because authors of the papers cited often did not indicate what type of landslide was present and because many of the landslides are "complex;" that is, more than one type of slope movement occurred. For each case, I arrived at a "best estimate" of landslide type based on a simplified approximation of the "Varnes landslide classification" (Varnes, 1978; Cruden and Varnes, 1996). In the case of complex landslides, I have noted the primary type of movement at the dam site. In cases where I have not been able to determine the specific type of movement, I have designated the type as "landslide." Nearly all of these "general" cases are located outside the United States because I was able to visit nearly all the U.S. sites to personally evaluate the landslide types. I have broken down the distribution as follows:

- Rock falls (including talus deposits)—20
- Slides in competent or "hard" rocks—60
- Slides in incompetent or "soft" rocks—109
- Earth and debris slides—25
- Rock and debris avalanches—3
- Debris/mud/earth flows, including *lahars* (volcanic debris or mud flows)—23
- Cambering and valley bulging—1
- "Landslides" (type unknown)—13

Typical well-indurated, competent, or "hard" rocks include igneous rocks; most metamorphic rocks; hard sedimentary rocks, such as limestones and hard sandstones; and competent volcanic rocks, such as andesite and basalt. Typical poorly indurated or incompetent rocks include shales, soft sandstones, soft volcanic tuffs, and weathered schists. Note that 169 of the 254 cases involve rock slides, in either competent (60 cases) or incompetent (109 cases) rocks. The large number of "soft-rock" slides is largely because of the great number of 10–50 m high dams that have been built on shales and other relatively incompetent sedimentary rocks in the Western United States. In the United States, the number of dams associated with "soft-rock" landslides is 78, as compared to 36 associated with "hard-rock" landslides. Outside the United States, 36 dams have interacted with "hard-rock" slides, versus 31 associated with "soft-rock" landslides. In the United States, numerous dams have been built on very large landslide masses or glide blocks that consist of hard rocks, usually basalts, that have slid intact on underlying softer volcanic or sedimentary materials. The largest of these areas is the Grand Mesa landslide complex in western Colorado, which is the site of dozens of dams and reservoirs, including 19 of the dams in this study.

Selected Case Histories of Dams on Landslides (by Landslide Type)

This section discusses notable cases in which dams have been built on landslides or landslides have occurred in foundations or abutments either during construction or after completion of the dam. Individual cases are organized by type of landslide.

Rock Fall (Including Talus Deposits)

Of the 20 cases in this category, only two (Mammoth Pool and Waterbury Dams, both in the United States) are dams that have been sited on large rocks that had fallen to the bottom of steep-walled gorges. The other 18 were cases in which a significant thickness (at least a few meters) of talus on an abutment slope was not removed, or was only partly removed, during construction. In most of these cases, an impervious core zone or trench was dug through the talus, but the mass was left in place under the outer shells of the dam. In several other cases that were reviewed, but not included in Appendix table A, existing talus was removed from the entire footprint of the dam. The main reason for removal of the talus was usually its high permeability. Selected examples of the 20 cases are discussed below.

- Mammoth Pool Dam—Mammoth Pool Dam (fig. 2) on the San Joaquin River in the Sierra Nevada Range of central California, United States, is a 125-m-high earthfill dam, which was completed in 1959 to produce hydroelectric power. As was obvious during early planning for the dam, the canyon originally

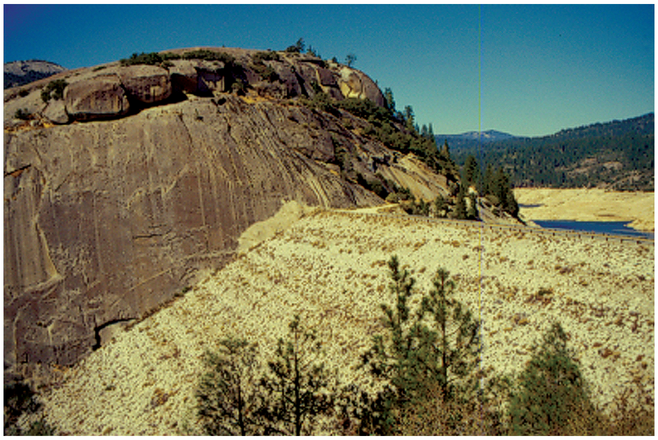


Figure 2. Mammoth Pool Dam, San Joaquin River, California, United States. Note the exfoliation sheets and blocks in the granodiorite that forms the right abutment. Photograph taken in 1998.

was dammed naturally by rock-fall deposits related to exfoliation of the granodiorite that formed the upper canyon walls. Some individual boulders in the bottom of the gorge were as large as 5,000 m^3 in size. Professor Karl Terzaghi served as the primary geotechnical consultant for this dam; his main function was to evaluate whether a water-tight dam could be built on these rock-fall deposits, and to decide what types of mitigative measures would control rock fall during construction or future operations of the dam. To ensure safety from rock fall, the remaining sheets of granodiorite on the upper slopes were removed or bolted to the canyon walls (Terzaghi, 1962; Goodman, 1993, p. 242–243). Blocks in or near the location of the cutoff trench at the core of the dam were removed or broken up by means of explosives. The cutoff trench was constructed through the rock-fall detritus to bedrock. Most boulders and rock fragments under the outer shells of the dam were left in place. Mammoth Pool Dam is performing satisfactorily with only minor seepage loss.

- Waterbury Dam—Waterbury Dam is a 57-m-high earthfill dam on the Little River, Vermont, United States. The dam was completed in 1938 but has been subject to foundation seepage since. Unknowingly, the dam was founded on detached rock slabs in a narrow gorge at the base of the dam (fig. 3). As noted by Saber and others (2001), “Detached rock slabs along the right (west) side of the gorge form a roof over a piping tunnel known to have been a piping path in the past, and capable of being a piping path in the future if injected filter materials are destabilized.” A grouting program to prevent seepage through the rock-fall zone was completed in 1985, but, apparently, some seepage continues.

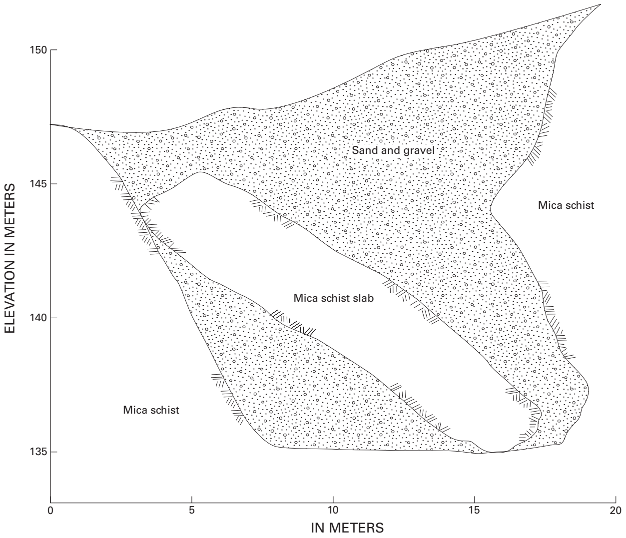


Figure 3. Cross section through the narrow gorge in the foundation of Waterbury Dam, Little River, Vermont, United States. The detached mica schist slab formed a “roof” over a potential piping path in the sand and gravel below. Modified from U.S. Army Corps of Engineers unpublished report (1988).

- Ancipa Dam—Ancipa Dam, a 105-m-high cellular concrete gravity dam on the Troina River of Sicily, Italy, was completed in 1953 to provide hydroelectric power and irrigation water. The dam’s right foundation and abutment have a thick talus cover. “At the right bank, the bedrock is reached by a concrete cut-off wall driven through the talus” (ANIDEL, 1961, v. 1, p. 300–306).

- Marmorera Dam—Marmorera (Castilleto) Dam in Graubünden Canton of southeastern Switzerland is a 91-m-high earthfill dam that was completed in 1954 to produce hydroelectric power. The valley wall that forms the left abutment and left end of the dam foundation is a large talus fan (mainly serpentinite fragments) underlain by alluvium and moraine material. Because of the heterogeneity of this foundation and abutment, three separate remedial measures were introduced during the original construction to reduce seepage (Rambert and Gavard, 1961; Schnitter, 1961):

1. An underground curtain wall of concrete was placed to bedrock through the alluvium and morainal deposits in the lower part of the foundation.
2. A cutoff grout curtain was placed through the pervious talus fan that formed the upper foundation and abutment. The grout was a mixture of colloidal clay and cement stabilized by a chemical agent. As would

be expected, the talus was found to be much more pervious near the surface than at depth.

3. A grout curtain was placed in the bedrock under the core of the dam.

Two successful examples of dams that have been built on talus-covered abutments in the Rocky Mountains of the Western United States are Taylor Park Dam in Colorado and Anderson Ranch Dam in Idaho.

- Taylor Park Dam—Taylor Park Dam is a 63-m-high earthfill dam on the Taylor River in the Rocky Mountains of Colorado, which was completed in 1937 to provide irrigation water for the area. It was recognized before construction that the right abutment of the dam was covered by a thick talus cone derived from overlying sedimentary rock cliffs (fig. 4). The talus mass consisted predominantly of boulder-to-cobble-size rock fragments with some fine-to-coarse gravel and sand. During construction, the talus was removed from under the center and upstream parts of the dam, but was left in place in the area extending from ~25 m downstream from the centerline to the downstream toe of the dam. The foundation was prepared by constructing three concrete cutoff walls, one located roughly along the centerline and the other two upstream. The remaining talus in the downstream part of the right abutment poses a very minimal threat of piping; however, thus far, in spite of some seepage, there has been no evidence of piping. The dam has had a long history of satisfactory performance.

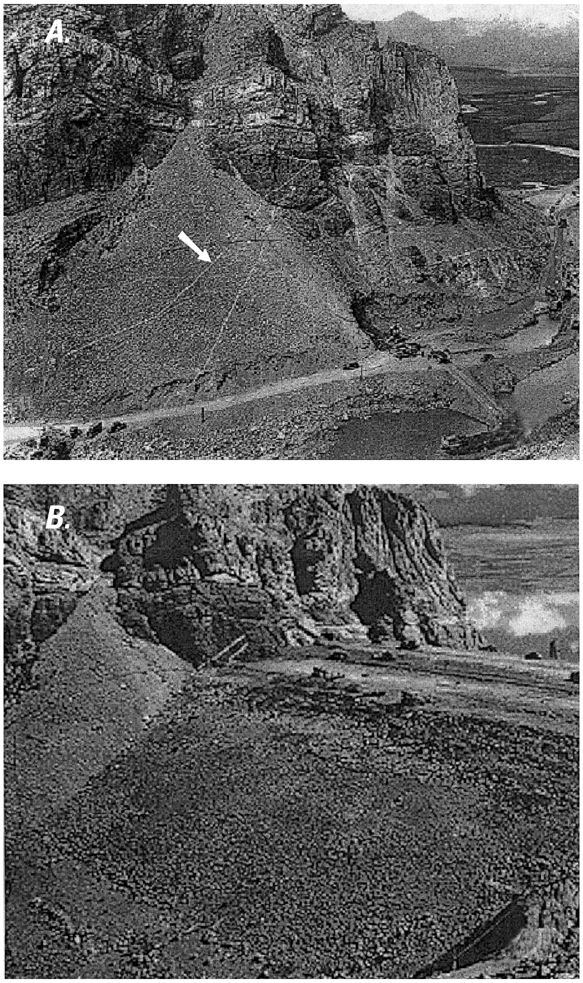


Figure 4. Views before (*A*) and after (*B*) construction of Taylor Park Dam, central Colorado, United States. Note the talus deposit that serves as the right abutment of the dam and the chalk line (marked by arrow) in photograph (*A*), which marks the location of the right end of the future dam on the talus cone. Photographs taken in 1937 by A.A. Whitmore, U.S. Bureau of Reclamation.

- Anderson Ranch Dam—Anderson Ranch Dam on the South Fork Boise River in southern Idaho is a 139-m-high earthfill dam completed by the Federal government in 1971 to provide irrigation water. Before construction, the right abutment was covered by a thick layer of basalt talus, which was removed under zone 1 (the interior, relatively impervious zone) of the dam, partially removed (“engineered”) under the upstream shell, and left in place under the downstream shell. Seepage from the right valley wall downstream from the dam apparently passes through this talus. In addition, in recent years a small landslide has occurred into the reservoir at the upstream edge of the “engineered” talus slope.

Slides in Competent Rock

As noted by numerous authors (for example, Wentworth, 1929), concrete dams, and especially arch dams, require competent rock foundations; while earthfill and rockfill dams can be founded satisfactorily on less-competent materials. However, this study notes 43 concrete dams that were built on pre-existing landslides or had landslides occur during or after construction. As would be expected, most of these concrete dams were built on what was originally thought to be competent rock. A total of 61 of the 254 dams in Appendix table A interact with slides in competent (“hard”) rock. Selected examples of these 61 dams are described below.

- Gross Dam—Gross Dam (fig. 5), Colorado, United States, is an example of a concrete-gravity dam that was founded on a pre-existing deep-seated slide in competent rock. Completed in 1955, this 104-m-high municipal water-supply dam is seated on deep-seated “gravity-slip surfaces” in both granite abutments (fig. 6) (Wahlstrom, 1974, p. 78–79). Although these “gravity faults” were closely watched during construction, they pose no hazard to the completed dam, which is expected to buttress any possible future movement. Thus, even though the dam is a relatively inflexible concrete structure, this type of slide was primarily a "textbook" case that posed no danger to the dam, and the dam continues to perform well.

- St. Francis Dam—Possibly the best known, and most infamous, of dams that have been built on what was thought to be competent rock, but was actually the toe of a pre-existing landslide, was St. Francis Dam in southern California, United States, a 62-m-high arch-gravity dam completed in 1926 to supply water to the city of Los Angeles. The presumed stable left abutment of this dam actually was the toe of a large, prehistoric landslide in schist bedrock. As the reservoir neared capacity in 1928, the dam suddenly failed, releasing a catastrophic flood that drowned 450 people (Outland, 1977). Preliminary investigations pointed to a fault in the right abutment as the cause of failure. Later, more comprehensive studies (Willis, 1928; Rogers, 1992, 1995, 1997) showed fairly conclusively, however, that failure began as reactivation of the schist slide in the left abutment (figs. 7 and 8). This is the only case noted in this study of a catastrophic dam failure caused by dam construction on a pre-existing landslide. The dam was never rebuilt.

Figure 5. Gross Dam, Colorado, United States, which supplies water to the city of Denver. The cross section in figure 6 shows gravity-slip surfaces in both abutments of the dam. Photograph taken in 2003.

- Beauregard Dam—Another major concrete dam that has experienced reactivation of a rock slide in an abutment is Beauregard Dam, a 132-m-high arch-gravity dam on the Dora di Valgrisenche River in northwestern Italy, which was completed in 1960 (ANIDEL, 1961, v. 1, p. 313–314). The left abutment for this dam is a massive rock slide in mica schist, which before construction overlaid a deep pocket of glaciofluvial sediments (fig. 9) (Desio, 1973, p. 901; Záruba and Mencl, 1982, p. 243–244). During the first filling of the reservoir, the landslide reactivated, attaining a displacement rate of 20 mm/month. As a remedial measure, some of the sediments were replaced by concrete. In addition, a watertight membrane was placed through the left abutment by cement injection. The dam is performing well.

- Dalešice Dam—Dalešice Dam, a 100-m-high hydroelectric-power rockfill dam on the Jihlava River in the Czech Republic, which was completed in 1979,

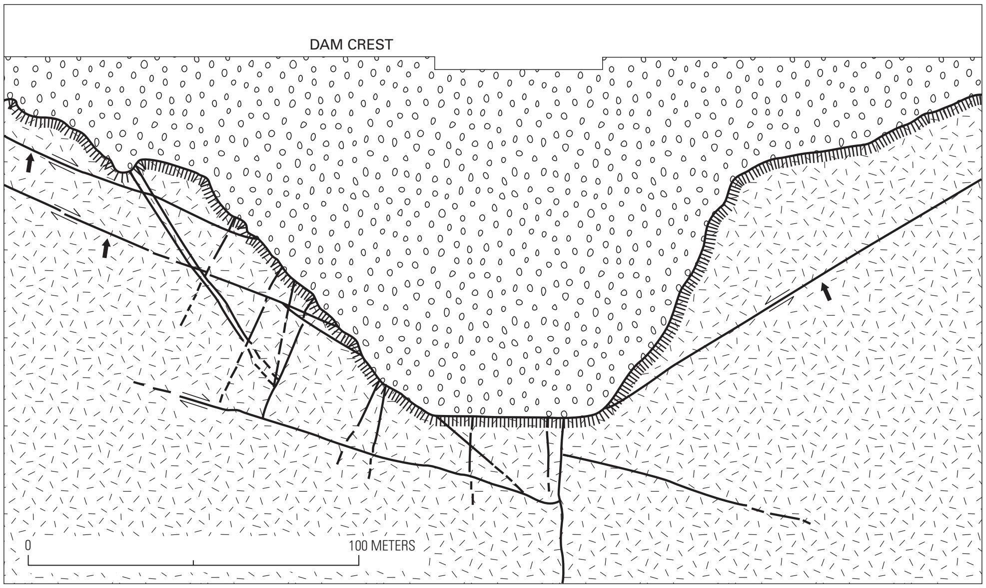


Figure 6. Gravity-slip surfaces (marked by thick arrows) in granitic foundation rocks at Gross Dam, Colorado Front Range, United States. Other faults of tectonic origin are geologically much older than the gravity-slip "faults." Modified from Wahlstrom (1974).

Figure 7. Looking upstream at the remains (center of photograph) of St. Francis Dam, southern California, United States, soon after its 1928 failure, which resulted in a catastrophic flood that killed about 450 people. The failure began in the toe of a large prehistoric landslide that formed the left abutment (right side of photograph); note fresh landslide scarps. Photograph taken in 1928, courtesy of Department of Geography, University of California at Los Angeles.

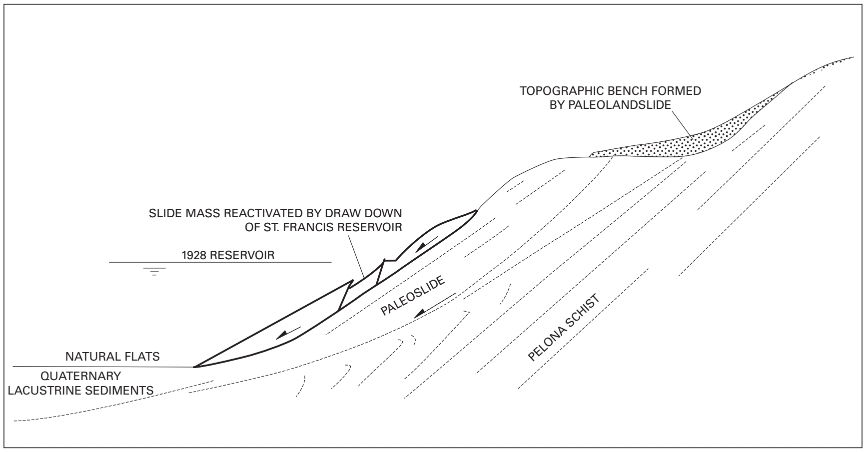


Figure 8. Cross section through the 1928 left-abutment landslide at St. Francis Dam, California, United States. Modified from Rogers (1995).

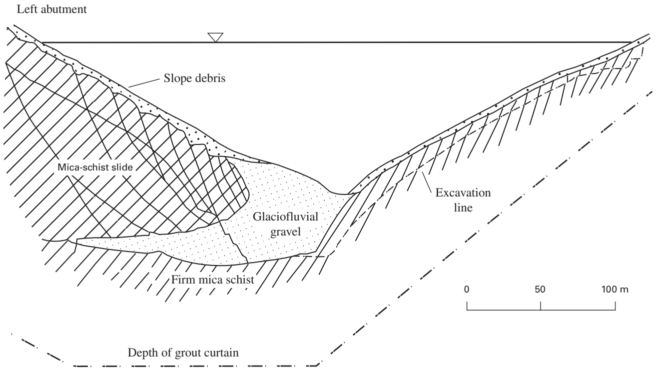


Figure 9. Cross section through the pre-existing rock slide that forms the left abutment of Beauregard Dam, northwestern Italy. Modified from Desio (1973, p. 901)

was founded on supposedly stable amphibolite and granulite. However, during excavation for the right abutment of the dam, failure occurred in schistose mylonite along a fault contact between the amphibolite and the granulite. The failure resulted in sudden movement of a 150,000 m^3 block of amphibolite along the mylonite zone (Mencl, 1977; Záruba and Mencl, 1982, p. 245–246) (fig. 10). As remedial measures, a temporary stabilizing berm was built at the toe of the slope and material was removed at the head of the slide. Subsequently, the slope was further stabilized by making horizontal benches from which anchors were installed into the firm granulite (Hobst and Zajíc, 1983, p. 399–401).

- Tablachaca Dam—Another well-known example of a concrete dam built on a pre-existing slide in competent rock is Peru's Tablachaca Dam (figs. 11 and 12), an 80-m-high concrete arch-gravity dam on the Mantaro River, a tributary of the Amazon River. This dam was placed in service in 1972 to produce about one third of Peru's electric power. During the late 1970s, it was noted that part of an ancient rock slide in phyllite, which formed the right abutment of the dam, had reactivated (probably because of the reservoir) and was moving slowly toward the dam (fig. 13) (Novosad, 1979; Novosad and others, 1979). A system of remedial measures, which included an earth berm at the toe of the slope (the toe of the berm is underwater), prestressed rock anchors, and drainage adits, were installed during the 1980s (Morales Arnao and others, 1984; Repetto, 1985; de la Torre and others, 1997) at an estimated cost of U.S. $40 million (1985 dollars). Since then, the dam has generally performed well; however, recently there has been renewed creep in the right abutment (Garga and de la Torre, 2004).

- Lake Harriet Dam—Another interesting concrete-arch dam case is that of Lake Harriet Dam, a 21-m-high dam (fig. 14) that was completed in 1923 to produce electric power for western Oregon, United States. The left abutment of this dam was thought to be stable basalt. However, this basalt abutment is part of the reactivated toe of a 50-km^2 landslide mass. During the early 1980s, cracks were noted in the dam due to compression from the left abutment. The problem was solved in 1985 by using the tremie process (underwater pumping through a pipe) to place a soil-bentonite "membrane" against the upstream face of the dam, and by constructing rockfill buttresses against both faces of the dam (Schroeder and others, 1988). Although the dam is currently performing well, the compressive

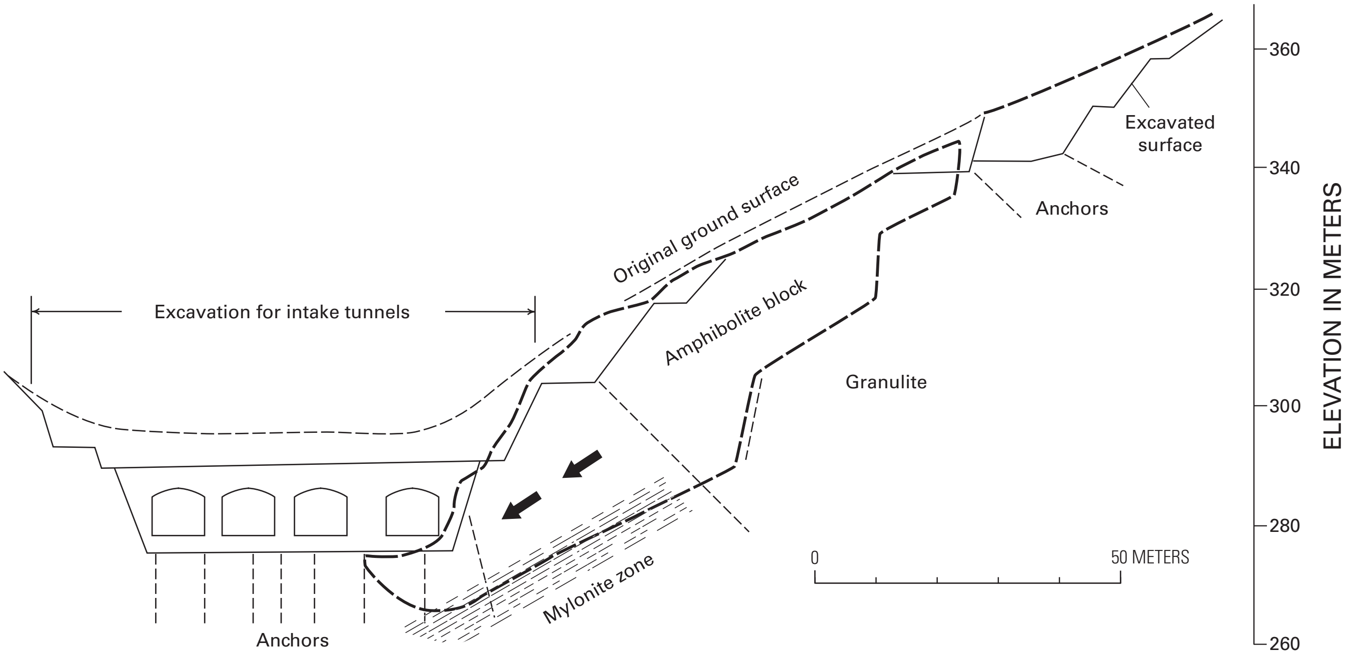


Figure 10. Simplified cross-valley cross section through Dalešice Dam, Jihlava River, Czech Republic. Construction caused reactivation of a rock slide of the amphibolite in the right abutment. This cross section shows locations of remedial excavations and rock anchors. Modified from Záruba and Mencl (1982, p. 246).

Figure 11. Oblique view of Tablachaca Dam, Peru. The preexisting rock slide in the right abutment is outlined by arrows. This slide was reactivated in the 1970s, probably because of infiltration from the reservoir. Photograph taken in 1982.

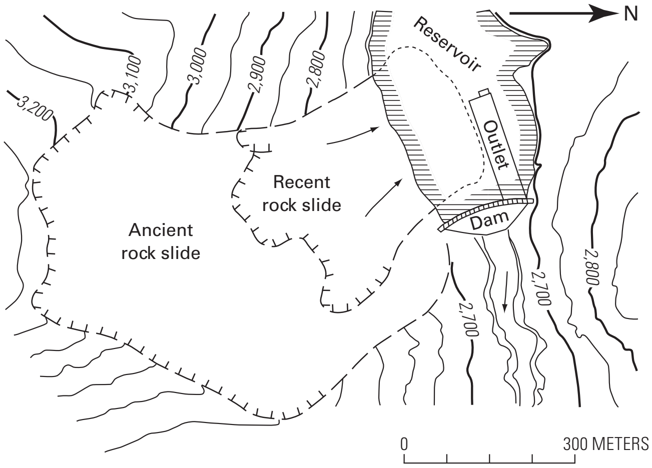


Figure 13. Map of rock slide at the right abutment of Tablachaca Dam, Peru. Shown is the recent, active slide that is a reactivation of the toe of a larger, ancient rock slide. Modified from Novosad (1979).

Figure 12. Looking upstream at the right-abutment landslide at Tablachaca Dam, Peru. Photograph taken in 1982.

Figure 14. Lake Harriet Dam, Cascade Range, Oregon, United States. The basalt that forms the left abutment of this dam is part of the reactivated toe of a 50-km^2 landslide mass. Photograph taken in 1999.

force of the landslide continues to act against the dam through the basalt abutment.

- Bonneville Dam—Another well-known example of a dam on a major rock slide is Bonneville Dam, a 60-m-high concrete gravity dam in the Columbia River Gorge of Washington and Oregon, United States. It was completed in 1937 for purposes of hydroelectric power production, navigation, and recreation. The Columbia River Gorge includes several large Holocene landslides in basalt underlain by less-competent volcanics (fig. 15) (Palmer, 1977). The right (Washington) abutment of this dam is part of the toe of the Bonneville landslide (figs. 16 and 17), the youngest element of the huge Cascade landslide complex (figs. 15 and 17) (Sager, 1989; Keech and Sanford, 1998; Schuster and Pringle, 2002). Although there have been minor surficial movements of the Bonneville landslide, its mass is so large and well-seated that the dam abutment and foundation are stable, and the dam continues to perform well.

- Durlassboden Dam—A European example is Durlassboden Dam, an 83-m-high structure in Austria, which was built on a large rock slide. The right abutment of this hydropower dam is on a large block of graphitic schists and quartzites that had slid down the right valley wall and sunk into valley deposits of glaciofluvial sands and gravels and lacustrine silts (Mignon, 1968; Záruba, 1974; Rienössl and Schnelle, 1976) (fig. 18). The abutment and foundation were subsequently sealed by a grout curtain that extends into silts about 50 m beneath the valley floor.

- Platoro Dam—Another example in the Western United States is Platoro Dam, a rockfill/earthfill dam on the Conejos River in the San Juan Range of southwestern Colorado, which was completed in 1951 to provide irrigation water for the area. The left end of this 50-m-high dam rests on a massive andesite slump block (length >1 km). Because of the large, well-seated mass of the block, there have been no stability or seepage problems, and the dam continues to perform well.

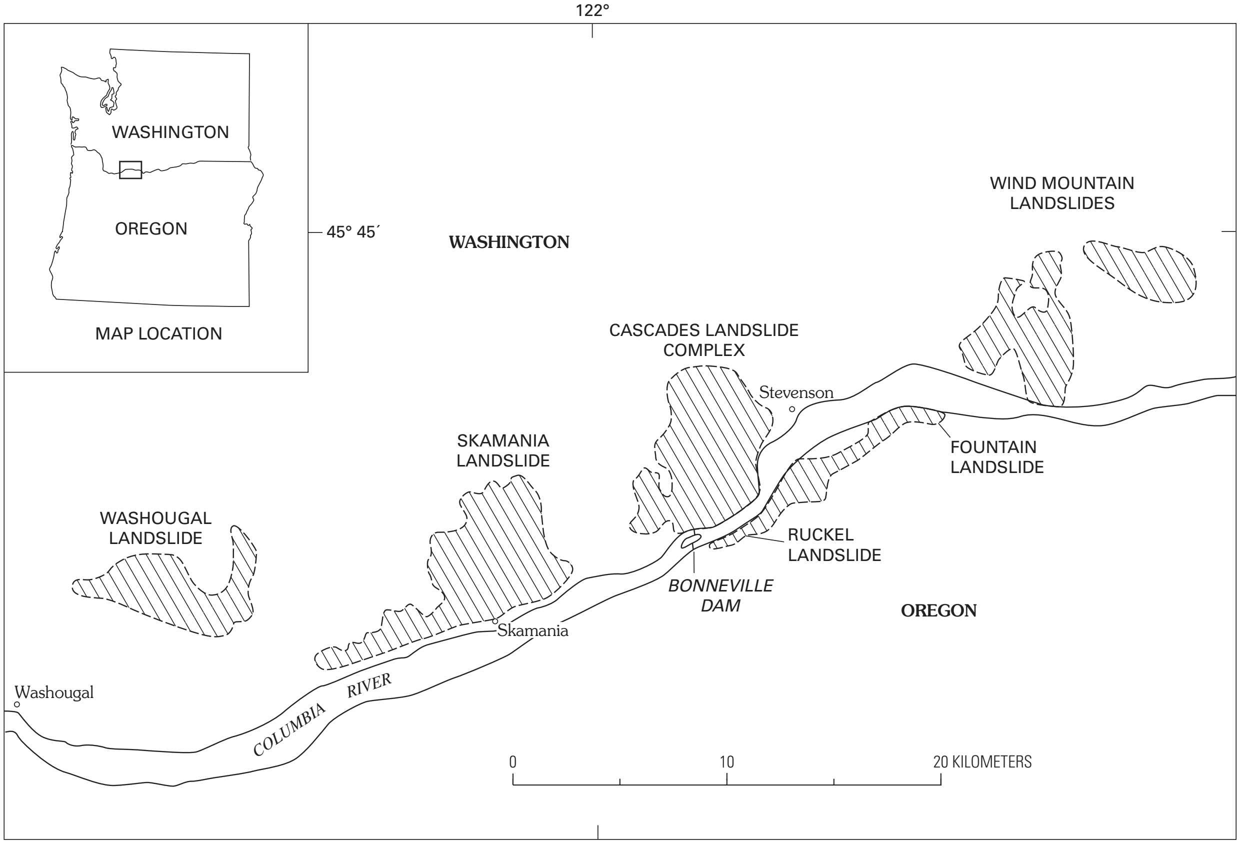


Figure 15. Major Holocene landslide deposits in the Columbia River Gorge, Washington and Oregon, United States, including the Cascades landslide complex, the youngest element of which is the Bonneville landslide (figs. 16 and 17). Note the location of Bonneville Dam. Modified from Palmer (1977).

Figure 16. Oblique aerial view of Bonneville Dam in the Columbia River Gorge, Washington and Oregon, United States. The right (Washington) abutment is the toe of the huge Bonneville landslide, which is the most recently active part of the Cascades landslide complex. Photograph by Derek Cornforth, Landslide Technology, Portland, Oregon.

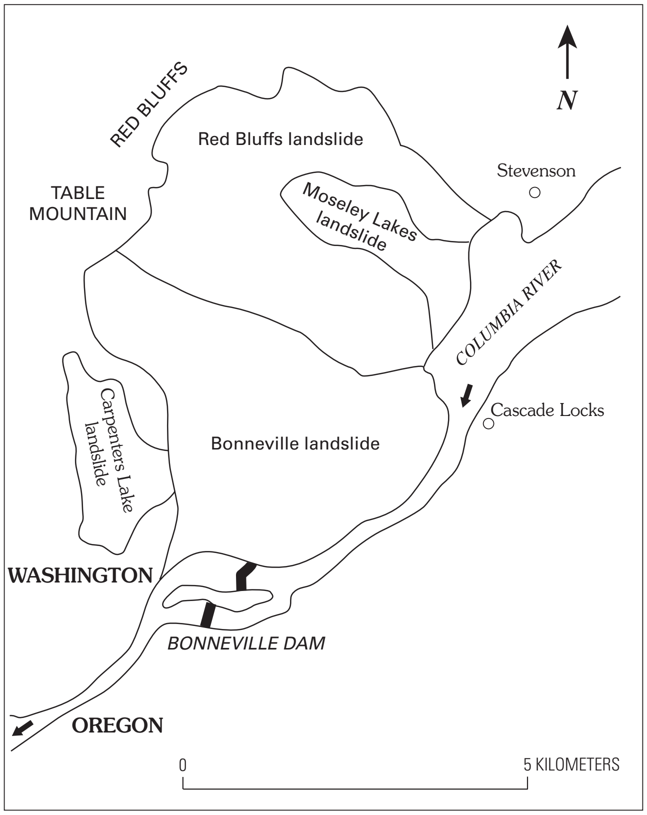


Figure 17. Map of the Cascades landslide complex and its components, which include the Bonneville landslide. Note the location of Bonneville Dam. Modified from Wise (1961).

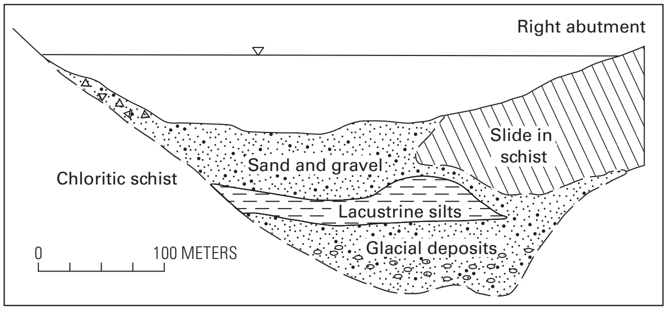


Figure 18. Simplified cross section through the rock slide in schist that forms the right abutment of Durlassboden Dam, Austria. Modified from Záruba and Mencl (1982, p. 243).

Occasionally, movement along pre-existing joints or faults in seemingly competent rock abutments is reactivated by dam construction. In many cases, any movement is halted by the buttressing effect of the dam itself. Movement of masses of competent rock along joints and fractures in this manner does not traditionally characterize the slipped rock masses as landslides. However, such movement of competent rock masses in this manner may create problems for dams similar to those caused by landslides. Two cases of dams that interact with this type of movement of rock masses are included in Appendix table A and are discussed below.

- Meishan Dam—An example is Meishan Dam, an 88-m-high concrete multiple-arch dam on the Shihe River, Anhui Province, China. This dam, which was completed in 1956 for purposes of flood control, irrigation, and hydropower, was founded on jointed granite, and, in 1962, movement occurred along joints in the right abutment (Qi, 1986; Chinese National Committee on Large Dams, 1987, p. 134–138). Apparently, these joints had exhibited some movement before construction. Remedial measures included installation of a grout curtain, an impervious membrane upstream of the abutment, anchors, and berms that served as buttresses.

- Tooma Dam—An Australian example is Tooma Dam, a 67-m-high, earthfill/rockfill dam constructed on the Tooma River of southeastern Australia to produce hydroelectric power. After completion of the dam in 1961, sliding was noted along joints in both abutments (Hunter, 1982; Fell and others, 1992). Remedial measures included rockfill buttresses, “dental” work in open joints (filling voids with cement grout or concrete), addition of a downstream grout curtain, and adding to the impervious zone of the embankment.

Slides in Incompetent Rock

One hundred and nine of the dams in Appendix table A were built on landslides in poorly indurated, relatively incompetent rocks. Most of the slides in this category have occurred in soft sedimentary rocks, mainly shales, mudstones, siltstones, and poorly indurated sandstones, and in weathered schists and weak volcanics. Embankment dams have commonly been constructed at sites where incompetent materials form dam foundations or abutments.

- Slezska Harta Dam—In the Czech Republic, Nechranice, Slezska Harta, Terlicko, and Zermanice Dams have all encountered problems with “soft rock” abutments. Especially well known are the problems in the shale left abutment of Slezska Harta Dam, a 65-m-high rockfill structure on the Moravice River, which was completed in 1997 for purposes of water supply and flood control. During construction of this dam, movement occurred in shale slide deposits that made up the left abutment (Novosad, 1990; Torner and Novosad, 1991). The stability problem was mitigated by excavation of slide material from the upper left slope, construction of a berm at the toe of the slope, and installation of surface and underground drains (Novosad and Novosad, 1993).

- Fruitgrowers Dam—An interesting example of a dam in the Western United States that was built on soft rocks is 17-m-high Fruitgrowers Dam, an earthfill dam built to provide irrigation water in western Colorado. The original Fruitgrowers Dam (11 m high) was constructed in 1898, but failed in 1937 due to “saturation and slipping” in the embankment at the spillway, which caused considerable flood damage to the small town of Austin, the Denver & Rio Grande Western Railroad, and a State highway (Engineering News-Record, 1937). The current dam was built in 1939, and its left abutment is on a large landslide in shale (fig. 19). Slow movement began in this shale mass in the late 1990s. This abutment is currently being closely monitored to determine if remedial measures will be needed, but otherwise the dam is performing well.

Soft sedimentary rocks form the abutments or foundations of several major dams in the Great Plains of central North America. In a few of these cases, pre-existing slides in soft sedimentary rocks of the valley walls have affected design and construction of major Canadian and U.S. dams. Two outstanding examples follow.

Figure 19. Fruitgrowers Dam, an irrigation dam in western Colorado, United States, showing apparent landslide topography in shale of the left abutment. Photograph taken in 1999.

- Gardiner Dam—Especially well known in Canada is the case of Gardiner Dam, an earthfill dam on the South Saskatchewan River in the central province of Saskatchewan. This 69-m-high dam was completed in 1968 for purposes of irrigation, water supply, and production of hydroelectric power. The shale left abutment of the dam included a large prehistoric slide (Ringheim, 1964; Jaspar and Peters, 1979). Local failure occurred in this abutment during construction, which led to excavation of much of the unstable shale under the central zone of the dam. To increase the stability of the abutment, the slopes of the remaining landslide deposit were flattened, and extensive berms were added as buttresses. The dam is performing satisfactorily.

- Oahe Dam—In the United States, several large dams on the upper Missouri River have been built on soft sedimentary rocks. One of these is Oahe Dam, a 75-m-high earthfill dam in South Dakota, which was completed in 1966. During construction, problems were encountered that were caused by pre-existing shale slides in the right abutment, and construction triggered a slide in the left abutment (Engineering Division, 1958; Knight, 1963). After the left-abutment slide occurred, 5.0 million m^3 of slide material was removed; of this, 3.5 million m^3 was placed at the toe of the slope as a berm that acts as a buttress. Part of a small slide remains in the right abutment. Both abutments are now completely stable because of the buttressing effect of the dam itself, and the dam continues to perform well.

Massive Rock Slides and Glide Blocks

In the Western United States, numerous dams have been built on massive landslides and glide blocks; these are cases in which entire dams and reservoirs lie on the large landslide masses. The best known of these cases are dams on landslides adjoining the Grand Mesa in western Colorado, on huge landslide masses in the mountains of north-central Colorado, and on the Malaga landslide in central Washington State.

- Grand Mesa landslide area—Rising to an elevation of 3,300 m, the Grand Mesa is an ~130-km^2 plateau remnant in western Colorado that is capped by continuous undisturbed upper Tertiary basalt flows that slope gently to the west. The basalt flows are underlain by a sequence of claystone, conglomerate, and sandstone, which overlies the Tertiary Green River Formation. Where these relatively weaker sedimentary rocks have failed, they have formed steep basalt cliffs, 30–150 m high, which surround the upland surface of the Grand Mesa (Yeend, 1969, 1973). A very irregular surface, produced by huge slumps and modified by glaciation, extends outward from the base of the basalt cliffs (Baum and Odum, 1996, 2003). Numerous lakes formed on this irregular surface as a result of the slumping and subsequent glaciation. The surface levels of many of these natural lakes have been raised by the addition of man-made dams. East of today's Grand Mesa, the landslide bench is extensive. Overall, this huge area of slump blocks extends about 70 km from east to west and 20 km from north to south, most of it lying to the east of the basalt remnant of the Grand Mesa (fig. 20).

  As became obvious early in the 20th century, the irregular surface topography of this large landslide bench was well-suited for the easy impoundment of snowmelt by dams and reservoirs. Thus, many dams and reservoirs were built on these landslides and intermingled glacial deposits. Appendix table A lists 19 irrigation, water supply, and/or recreation dams that are founded on the Grand Mesa landslide bench, ranging in structural height from 10–26 m (there are no larger dams in the Grand Mesa area). Noted in Appendix table A as being on this landslide bench or on rockfall deposits from Grand Mesa cliffs are the following Colorado dams: Atkinson, Big Beaver, Bonham, Cedar Mesa, Eggleston, Goodenough #2, Granby #12, Hogchute, Kehmeier, Kennicott Slough, Kiser Slough, Knox, McKoon, Monument #1, Overland #1, Park, Vela, Ward Creek, and Young's Creek Nos. 1 and 2. Several of these dams have had foundation or abutment seepage problems, often requiring repairs, but none has manifested stability problems or pose downstream hazards.
- Mountains of north-central Colorado—North-central Colorado includes several subranges of the Rocky Mountains, in which large rock slides consisting of resistant rocks (usually volcanics) overlying softer rocks (usually shales, siltstones, and soft sandstones) are common. These rock slides often occurred as massive landslides from the valley walls upon retreat of late Pleistocene valley glaciers. They have formed

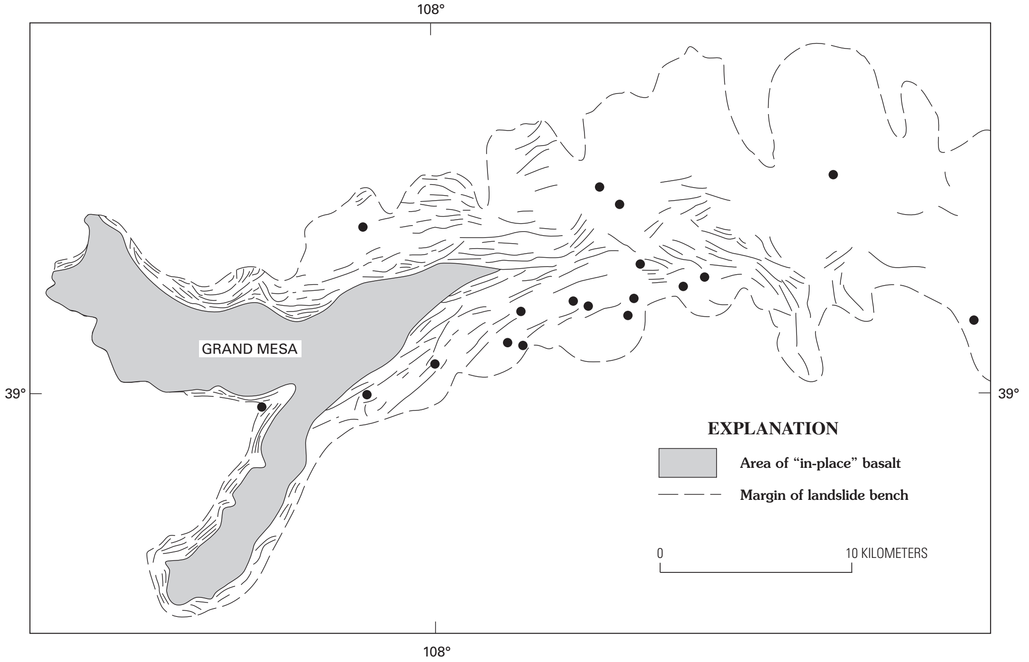


Figure 20. Locations of 18 dams (solid circles) on landslide bench and slump-block landslides derived from the basalt plateau of the Grand Mesa, western Colorado, United States. One other dam (Overland Dam) is located on these landslide deposits, less than 2 km east of the eastern border of this figure. The landslide map has been modified from Yeend (1969).

constrictions in high mountain valleys, resulting in seemingly opportune sites for the location of dams. Examples of these in Appendix table A include Stillwater #1, Upper Stillwater, Yamcolo, Poose Creek, and Sheriff Dams, which are irrigation and recreation dams located in valleys that drain from the northeast slopes of the Flattop Mountains that consist of Tertiary basalts overlying shales and sandstones. A similar example from Appendix table A, Joe Wright Dam, is a large water-supply dam on eastward-flowing Joe Wright Creek in the Colorado Front Range. These dams are all performing well.

Three other dams and their reservoirs in north-central Colorado, which are included in Appendix table A, are located entirely on large glide blocks in soft rocks. Jones #2 Dam, a 12-m-high earthfill dam built in 1887, which impounds the main water-supply reservoir for the town of Kremmling, lies on a massive prehistoric 16-km^2 glide block in shales and sandstones of the Niobrara and Dakota Formations (Barclay, 1968, p. 157; Izett and Barclay, 1973; Madole, 1991a). D.D.&E. Wise (Aldrich Lake) Dam, a 12-m-high earthfill irrigation dam, lies on the eastern edge of a massive 16-km^2 landslide in Mancos Shale (Madole, 1989). Lower Cogdill Dam is a 12-m-high earthfill irrigation dam that was constructed in 1956. The dam and reservoir lie entirely on an 18-km^2 glide block overlying Lewis Shale and Mesaverde Group sandstones and shales on the west slope of the Elkhead Mountains in northwestern Colorado (Madole, 1982). Minor seepage issues from toe drains at Jones #2 Dam. Lower Cogdill and D.D.&E. Wise Dams have shown no distress related to their landslide foundations and abutments, and overall all three dams continue to perform satisfactorily.

Matheson Dam, an 18-m-high irrigation dam, was built in 1951 on the northeast edge of an 18-km^2 landslide mass (Tertiary volcanics overlying Morrison Formation shales and sandstones) in the Rabbit Ears Range northeast of Kremmling (Madole, 1991a). There has been some seepage through the landslide right abutment of this dam, probably related to the landslide materials; otherwise the dam is performing well.

- Malaga landslide area—The Malaga landslide, a large glide block on the west side of the Columbia River near Wenatchee, Washington, United States, consists of basalt that overlies softer volcanics and sedimentary rocks. Its irregular surface has served as a site for several small dams. Qualifying as large dams are Stemilt Main Dam (height, 20 m) and Upper Wheeler Dam (height, 20 m), two irrigation dams that are founded entirely on this large glide block. The Stemilt Main Reservoir leaked considerably through the landslide material until an impervious geosynthetic membrane was successfully emplaced in 1986. Minor leakage at the left abutment was later remedied by installation of drains. Minor leakage at the left abutment of Upper Wheeler Dam also has been controlled by installation of drains.

Earth and Debris Slides

Twenty-four of the 254 dams tabulated in this study have earth- or debris-slide material in the foundation or abutments. With two important exceptions, these were embankment dams. The exceptions are two concrete dams: Grand Coulee Dam, United States, and Vodo Dam, Italy. Some examples of the 24 dams in Appendix table A are described below.

- Grand Coulee Dam—Grand Coulee Dam (fig. 21) is a 168-m-high concrete-gravity structure on the Columbia River in Washington State, United States. This dam, at one time the largest (in volume) concrete dam in the world (its volume recently has been exceeded by that of China's Three Gorges Dam), was completed in 1942 to provide irrigation water, hydroelectric power, and flood control for the U.S. Pacific Northwest. Granite is the main foundation material for Grand Coulee Dam, but the right abutment included unstable glacial varved clays. Preparation of the right abutment reactivated movement of these clays (Irwin, 1938). The clays were stabilized by flattening the abutment slope, construction of a timber-crib retaining wall, and freezing the soil upslope from the wall by installation of a system of pipes that carried brine at below-freezing temperatures (Gordon, 1937). The slide area was then buttressed by the right end of the dam. This abutment was subsequently removed in 1967–81 when the dam was lengthened to accommodate the third powerplant. Thus, the dam no longer abuts a landslide and is performing well.

Figure 21. Grand Coulee Dam, eastern Washington State, United States. In 1969, the original landslide-prone glacial-soil right abutment was removed to make room for the second powerplant at the right end of the dam (left edge of photo). Photograph taken in 1999.

- Vodo Dam—Vodo Dam on the Boite River in the northern Italian Province of Veneto is a 42-m-high concrete domed-arch dam that was built in 1960 to provide hydroelectric power. Its left abutment has been described as consisting of “morainic materials and alluvial landslides” (ANIDEL, 1961, v. 1, p. 320). To prevent movement of these materials during construction, a diaphragm, consisting of overlapping piles in reinforced concrete, was placed in the abutment through a bentonitic-slurry trench, and there have been no problems since.

- Lake Sherburne Dam—Two examples of earthfill dams that have been built on earth slides are located in the State of Montana, United States; both were built on unstable glacial deposits. The better-known of these is Lake Sherburne Dam, a 33-m-high earthfill dam on Swiftcurrent Creek at the northeastern edge of Glacier National Park. This dam was completed in 1921 to provide irrigation water for eastern Montana. Apparently, it was known at the time that both valley walls consisted of massive landslides derived mainly from glacial deposits (Carrara, 1990; Whipple, 1992). Although the right abutment appears to be relatively stable, the left abutment is surrounded by a large unstable slide. The original foundation preparation included installation of three continuous cutoff trenches into stable till across the valley floor (Lowe, 1988). Prior to 1960, movement of the left abutment destroyed the original spillway, which was then moved to the right end of the dam. The left abutment remains unstable; its movement is being monitored regularly.

- Hyalite Dam—Hyalite Dam in southwestern Montana is a 38-m-high earthfill dam that was completed in 1951 to provide water for irrigation and water supply. The left abutment of this dam consists of mixed landslide and glacial deposits made up of clay, silt, sand, poorly sorted gravel, rock fragments, conglomerate, and boulders. There have been no problems with stability; however, seepage through this abutment material has been a continuing problem. Thus, during the 1990s, a compacted earth liner was placed at the left end of the dam to reduce the seepage. The dam is now performing well.

Rock and Debris Avalanches

Only three of the 254 dams in Appendix table A have been in contact with rock or debris avalanches. These three are Parangana, Cheakamus, and Smith and Morehouse Dams.

- Parangana Dam—Parangana Dam is a 53-m-high rockfill structure on the Mersey River on the island of Tasmania, southeastern Australia. The dam was completed in 1968 to produce electric power for the island. Debris-avalanche deposits more than 50 m thick form part of the dam’s foundation, and its left abutment is in talus (fig. 22) (Paterson, 1971; Thomas, 1976, p. 156; Fell and others, 1992, p. 140–141). Apparently, there have been no difficulties with the debris-avalanche foundation or the talus abutment.

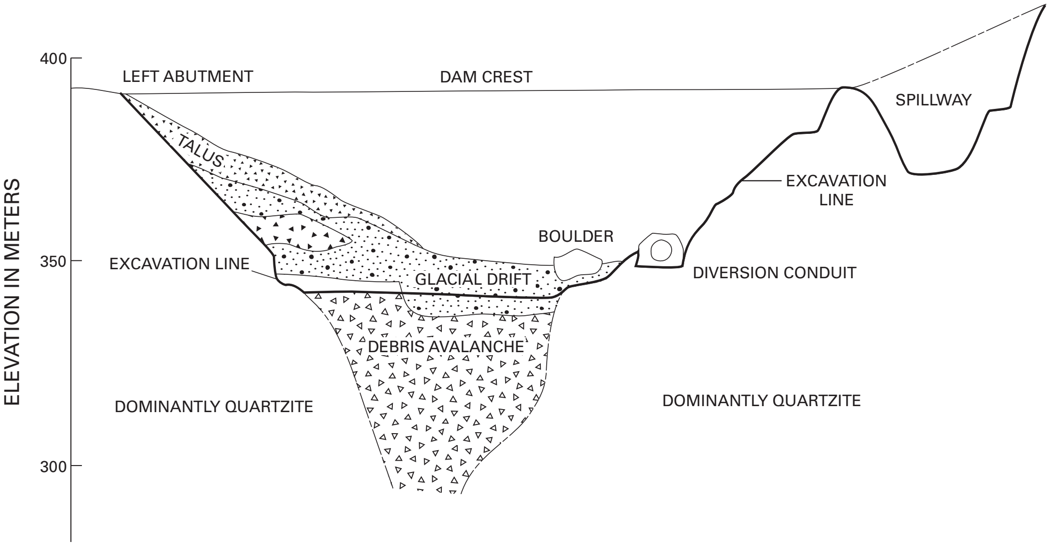


Figure 22. Cross section through the Parangana Dam site, Victoria, Australia, showing debris-avalanche deposits in the foundation and left abutment of the dam and talus deposits in the left abutment. All deposits above the excavation line were removed during construction. Modified from Paterson (1971).

Figure 23. Oblique aerial view of Cheakamus Dam, British Columbia, southwestern Canada. The foundation of the dam is mainly Rubble Creek Wash, a debris avalanche–debris flow deposit (see fig. 24). Photograph taken in 1999 by BC Hydro, Burnaby, British Columbia.

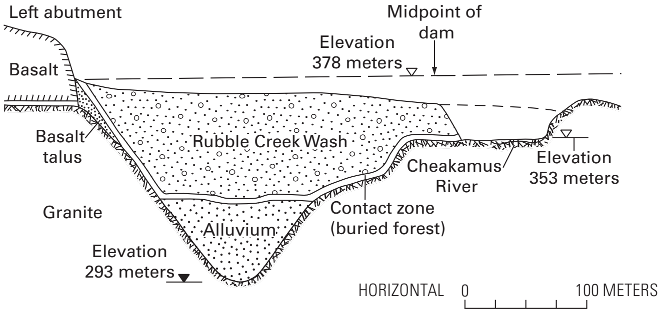


Figure 24. Cross section through the site of Cheakamus Dam, British Columbia, southwestern Canada, showing the location of the Rubble Creek Wash, the remains of an 1855–56 debris avalanche–debris flow deposit, on which the dam was built. Modified from Terzaghi (1960b).

- Cheakamus Dam—Professor Karl Terzaghi served as the geotechnical consultant for Cheakamus Dam, a 28-m-high earthfill/rockfill hydropower dam, which was built in 1957 in southwestern British Columbia, Canada (fig. 23). The Cheakamus River valley at the site is partially filled with materials known as “Rubble Creek Wash” (fig. 24), the deposits of a large debris avalanche–debris flow that occurred in 1855–56 (Terzaghi, 1960a,b; Moore and Matthews, 1978). The permeability and stability of these deposits were approved before construction. The only hazard facing Cheakamus Dam and Reservoir seems to be the possibility of another debris avalanche coming from The Barrier, a volcanic mass at high elevation upstream. Such an avalanche might enter the reservoir at high velocity, and could possibly cause overtopping of the dam.

- Smith and Morehouse Dam—In the United States, the only dam known to have been built on a pre-existing debris-avalanche deposit is the 25-m-high Smith and Morehouse Dam, an earthfill structure that was completed in 1988 to provide irrigation water to north-central Utah. The entire dam foundation is a large avalanche (age ~4,000 yr B.P.) of sedimentary rock and glacial debris that filled Smith and Morehouse canyon to a depth of about 60 m. Although the dam was built on this debris avalanche, a cutoff key placed through the debris increased the strength and imperviousness of the foundation.

Debris, Mud, and Earth Flows

Debris, mud, and earth flows, including flows of volcanic origin, make up the foundations and/or abutments of 24 of the 254 dams listed in Appendix table A. Of these, 17 are conventional debris, mud, or earth flows, and seven are flows of volcanic origin, also known by the Indonesian term *lahars*. Flow deposits usually are stable, but can be pervious enough to allow seepage through a dam’s foundation or abutments. This can pose possible problems for traditional dams. However, a few of the cases noted in this study are debris-retention or sediment-retention structures (also known as *check dams* or by the Japanese term, *sabo* dams); for these cases, permeability of the foundation is not a negative factor because these dams are intended to intercept only the solid fractions of the debris flows, not the water. Some examples of the 24 dams are described below.

Several dams in the Pacific Northwest of Canada and the United States have been built on flows, both regular and volcanic. These include Seymour Falls, Mud Mountain, and Swift Dams and the North Fork Toutle River sediment-retention structure.

- Seymour Falls Dam—Seymour Falls Dam on the northern outskirts of Vancouver, British Columbia, Canada, is a 30-m-high earthfill/concrete water-supply dam that was completed in 1961. The right abutment of this dam is a debris-flow cone from a tributary stream (Ripley and Campbell, 1963). The cost of an impervious cutoff through the debris cone to bedrock was considered to be prohibitive. Instead, an extensive impervious upstream blanket was installed to minimize seepage through the debris-cone abutment and the foundation (Heidstra and others, 1995).

- Mud Mountain Dam—Several major dams have been built on debris flows or mud flows (lahars) that originated from volcanoes in the Cascade Range of southwest Washington State, United States. Mud Mountain Dam is a 130-m-high earthfill flood-control dam that

Figure 25. Aerial-oblique view of Mud Mountain Dam, western Washington State, United States. At both banks of the White River, the dam abuts into a Pleistocene mud-flow (lahar) deposit from Mount Rainier volcano. Photograph taken in 1979 by U.S. Army Corps of Engineers.

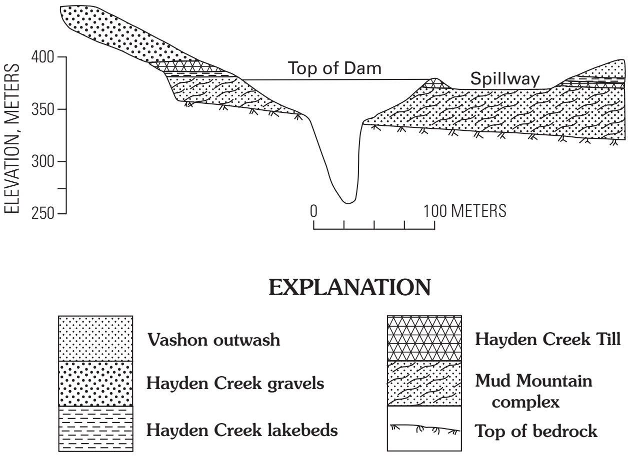


Figure 26. Cross section through the site of Mud Mountain Dam, Washington State, United States, showing the Mud Mountain complex (Pleistocene mud-flow deposits) in both abutments. Modified from Galster (1989b).

was completed in 1948 on the White River, a glacial stream from Mount Rainier (fig. 25). At both banks of the river, the dam abuts Pleistocene mud-flow deposits (Mud Mountain complex) (fig. 26) from Mount Rainier, which at the time of construction were thought to be glacial debris (Galster, 1989b; Eckerlin, 1992, 1993). Fortunately, these deposits are nearly impervious and are generally stable, particularly because they are buttressed by the dam. The only difficulties at this site have involved slides along the reservoir shore, which have not directly affected performance of the dam.

Figure 27. Aerial view of Swift Dam, Lewis River, western Washington State, United States, showing forested debris-flow deposits that form the right abutment of the dam (see fig. 28). Photograph by Lynn Topinka, U.S. Geological Survey.

- Swift Dam—Farther south in the Cascade Range of Washington State, two hydropower dams have been built on prehistoric lahars in the valley of the Lewis River, a glacial stream from the southeastern slopes of the cone of Mount St. Helens. The upstream structure is Swift Dam (fig. 27), a 126-m-high earthfill dam that was completed in 1958. Swift Dam’s right abutment and foundation are a thick, well-consolidated volcanic debris flow from a prehistoric eruption of Mount St. Helens (fig. 28) (Jensen, 1981; Tilford and Sullivan, 1981; Bliton, 1989). In the channel, an open-cut excavation for an impervious cutoff was made through this debris-flow material to a depth of about 30 m. Sheet piling was then driven to bedrock from the bottom of the trench (~25 m). A positive seal was formed by a grout curtain ranging in depth from 6–30 m and reaching into volcanic bedrock (Lowe, 1988). The right end of the dam was built on the lahar abutment with a drainage gallery to intercept any seepage. The system is operating successfully.

- Yale and Yale Saddle Dams—Yale Dam, a 98-m-high earthfill structure, also on the Lewis River, approximately 20 km downstream from Swift Dam, was completed in 1953. As is the case for Swift Dam, the Lewis River valley at the Yale Dam site was partly filled by prehistoric lahars from Mount St. Helens. A geologic map by Tilford and Sullivan (1981) shows the distribution of these lahar deposits at and near the damsite (fig. 29). The lahar deposit was excavated from under the impervious core of the dam; however, the papers cited do not make it clear whether it remains under the outer shell. Three kilometers north of Yale Dam is Yale Saddle Dam, a 12-m-high earthfill structure that helps to impound Yale Reservoir; this saddle dam is founded entirely on lahar deposits. Neither dam has shown dis-

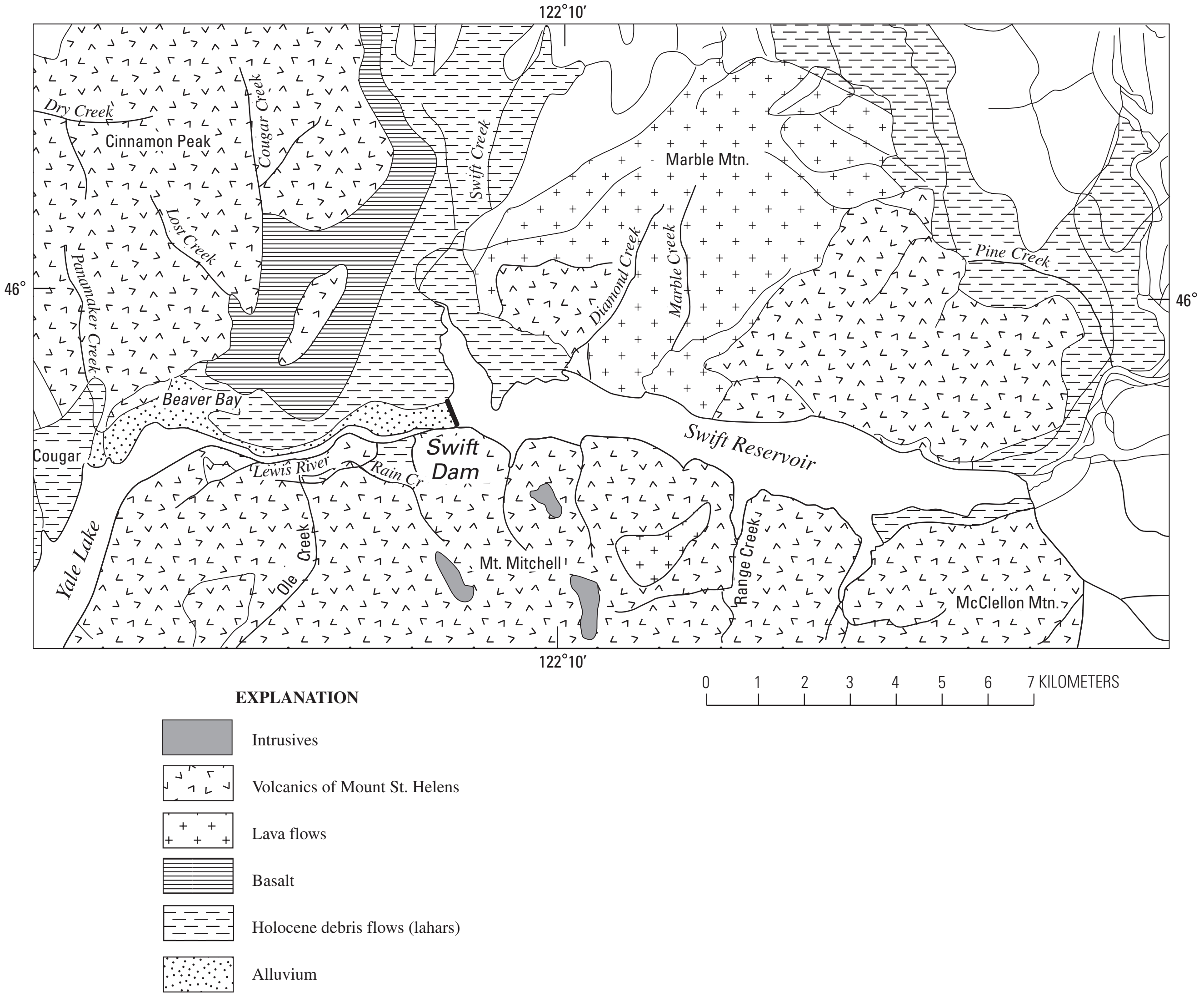


Figure 28. Geologic map of the area around Swift Dam, Washington State, United States, showing the distribution of Holocene debris flow (lahar) deposits that form the right abutment of the dam. Modified from Tilford and Sullivan (1981).

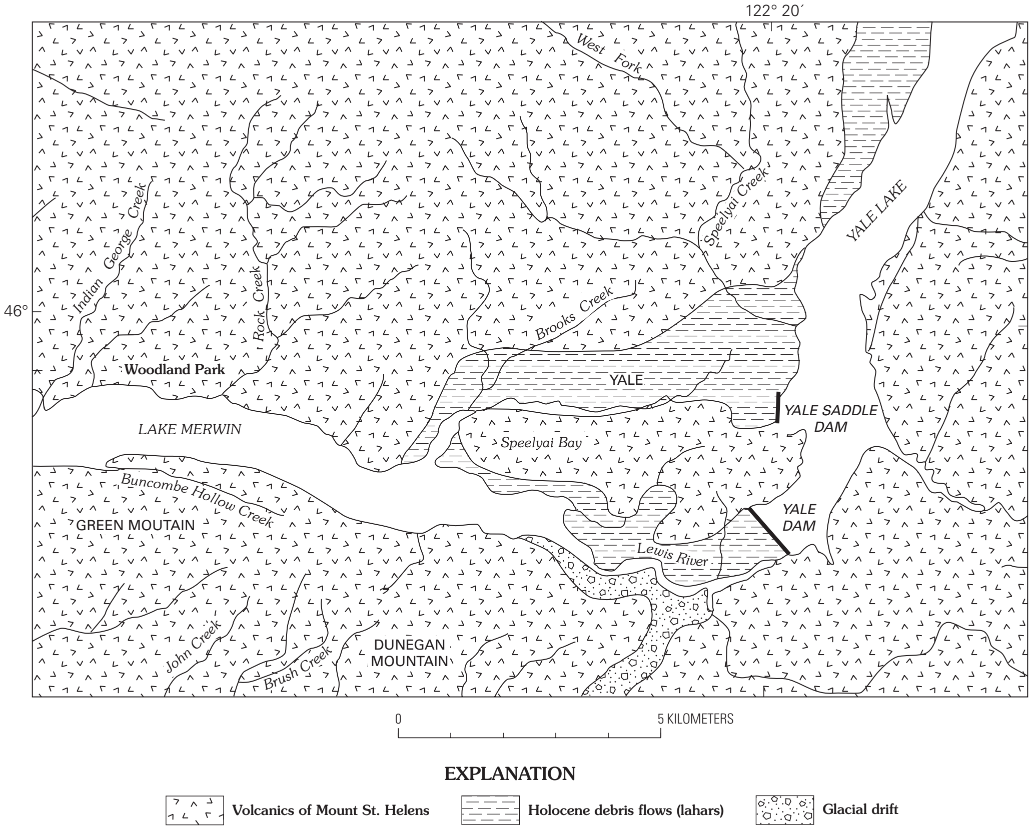


Figure 29. Geologic map of the area around Yale Dam and Yale Saddle Dam, Washington State, United States, showing the distribution of Holocene debris-flow (lahar) deposits that form the dams' foundations and abutments. Modified from Tilford and Sullivan (1981).

tress due to the debris-flow materials in the foundation or abutments, and they continue to perform well.

- North Fork Toutle River sediment-retention structure—Another dam on Mount St. Helens debris-flow deposits is the sediment-retention structure (SRS) built in 1988 on the North Fork Toutle River to retain debris-flow material that is washed from the surface of the 1980 debris avalanche, as well as any future debris flows that might come down the valley (Schuster, 1989). This 73-m-high earthfill dam (fig. 30) was constructed on at least 30 m of debris-flow material from the 1980 eruption and previous eruptions of Mount St. Helens. The dam is stable, and thus far is performing well (Bernton, 2000). The debris-retention function of this dam was augmented by the 1984–85 construction of an outlet tunnel from debris-avalanche-dammed Spirit Lake, the source of the North Fork Toutle River (Sager and Budai, 1989). This 2.6-km-long bedrock tunnel was built to prevent overtopping and failure of the debris-avalanche dam, which could have resulted in a catastrophic outburst debris flow, the volume and force of which might have overwhelmed the planned debris-retention structure.

Medeo Dam on the Malaya Alma-Atinka River and an unnamed dam on the Bolshaya Alma-Atinka River upstream from the city of Almaty in Kazakhstan are two other very successful debris-retention dams that have been founded on preexisting debris flows. Both were built to protect Almaty from the catastrophic debris flows that had entered the city from the Tien Shan Range every few years.

- Medeo Dam—The original 110-m-high Medeo Dam (fig. 31) on the Malaya Alma-Atinka River was built in 1968–69 by setting off explosive charges in the valley walls to form a man-made "landslide" dam that is founded on valley-bottom debris-flow deposits (Yesenov and Degovets, 1979, 1982). In July 1973, Medeo Dam retained a debris flow with a volume of about 5.5 million m^3 and maximum discharge of 10,000 m^3/sec that came from the outburst of a moraine-dammed lake on the upper Malaya Alma-Atinka River (Yesenov and Degovets, 1982; Popov, 1999). As a result, the retention basin of the Medeo Dam was nearly filled.

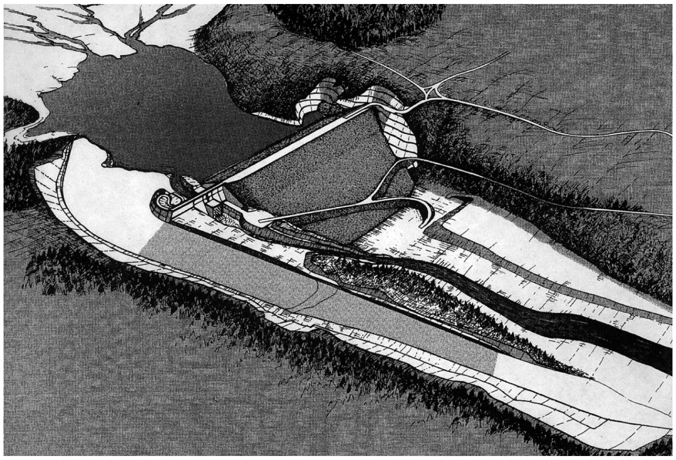


Figure 30. Sketch of the earthfill sediment-retention dam (SRS Dam) on the North Fork Toutle River, southwestern Washington State, United States. This dam, which was constructed in 1988 to intercept sediment and debris washed downstream from the debris avalanche triggered by the 1980 eruption of Mount St. Helens, is founded on debris-flow deposits (Schuster, 1989). Sketch by U.S. Army Corps of Engineers.

Figure 31. Medeo Dam, a debris-flow retention structure on the Malaya Alma-Atinka River in Kazakhstan, which is founded on debris-flow deposits. Photograph taken in 2001.

To contain future flows, the original earthfill dam was raised to a height of 150 m by traditional construction methods, providing a new retention basin with a volume of 12.6 million m^3.

- Unnamed debris-retention dam on the Bolshaya Alma-Atinka River—In 1982, a 40-m-high cellular reinforced-concrete dam (fig. 32) was built on debris-flow deposits in the valley of the Bolshaya Alma-Atinka River north of Almaty for the same debris-retention purpose as Medeo Dam. The retention-basin volume of the Bolshaya Alma-Atinka Dam is about 14.5 million m^3 of debris-flow material (Yesenov and Degovets, 1982).

Figure 32. Photograph of construction of a cellular reinforced-concrete debris-retention dam on the Bolshaya Alma-Atinka River of Kazakhstan. This 40-m-high dam, which was built in 1981–82 to protect the city of Almaty from the many debris flows from the Tien Shan Range, is founded on debris-flow deposits. Photograph taken in 1981 by D.J. Varnes, U.S. Geological Survey.

There are many debris-flow retention dams (sabo dams) in China, Indonesia, and Japan. Most of these are small check dams and most have been built on bedrock. The following are two examples of debris-flow-retention dams that have been built on landslides.

- Hunshui Gully debris-retention dam #4—An example from Yunnan Province, China, which qualifies as a "large dam" that was built on pre-existing debris-flow deposits is the 16-m-high Hunshui Gully debris-retention dam #4, a stone and concrete structure that was completed in about 1979–81 (Li and Luo, 1981; Zhang and others, 1985). This dam is one of a series of debris-retention structures built from 1978 to 1981 to intercept nonvolcanic debris flows on tributaries of the Xiao River (itself a tributary of the Yangtze River).

- Jinnosuke #5 sabo dam—An example from Ishikawa Prefecture, Japan, is 17-m-high Jinnosuke #5 sabo dam, which is the largest of more than 50 sabo dams built on a pre-existing slide in altered sandstone, shale, and rhyolite in the valley of the Tedori River (Fukuoka and Taniguchi, 1961; Ohta and others, 1996; Wang and others, 2003; Okuno and others, 2004). The original Jinnosuke #5 Dam has moved about 5 m since it was built in 1925, and was recently rebuilt as a new Jinnosuke #5. There are several other dams in the valley that are 10-m high or higher; even though these dams are slowly moving, all are successfully fulfilling their debris-retention function.

Of the many other debris-retention structures in these countries, a few undoubtedly are large dams that have been built on debris-flow foundations. However, I don't have sufficient information on these dams to include them here or in Appendix table A.

Cambering and Valley Bulging

Cambering and valley bulging have been noted in England as valleyward toppling of blocks of periglacial soils (Hutchinson, 1988). According to Cruden and Varnes (1996), a camber in rock may be described as a "relict, complex rock spread-rock topple." When occurring in periglacial soils, it would be known as a *relict, complex soil spread-soil topple.*

- Empingham Dam—During construction in 1975 of Empingham Dam, a 40-m-high earthfill water-supply dam in northern England, cambering and valley bulging in "boulder clay" (glacial till) were encountered in the foundation excavation (Horswill and Horton, 1976). The cambering and resulting valley bulging had no negative effects on dam construction or performance.

Problems Encountered Due to Interaction Between Dams and Landslides

Landslides in dam foundations or abutments may lead to instability of the dam or seepage within these units. Example case histories in which these problems have occurred are discussed below.

Abutment and Foundation Instability

Of the total of 254 dams in Appendix table A, 78 encountered abutment-slope or foundation movement either during construction (43 cases) or after completion of the dam (35 cases). For most construction-triggered failures, all or most of the active material was removed. In a few cases, it was left in place and stabilized, often by the buttressing effect provided by construction of berms or by the dam itself. There are only a very few known cases in which postconstruction movement affected or threatened the overall stability of the dam; St. Francis Dam (discussed earlier) and B.F. Sisk Dam, both in California, United States, are outstanding examples.

- B.F. Sisk (San Luis) Dam—An excellent example of landslide activity in an abutment after construction is B.F. Sisk (San Luis) Dam in central California. This 116-m-high earthfill dam, which was built for irrigation, hydroelectric power, and recreation, was completed in 1967. During drawdown in September 1981, a slide originated in "hard clay" slopewash of the left abutment and passed through the upstream face of the dam (Von Thun, 1985) (fig. 33). The slide moved about 20 m. The main mass of the dam remained stable, and the reservoir was not threatened. Remedial measures consisted of construction of a buttressing berm at the upstream toe of the dam and reconstruction of the upstream face.

In addition, three cases of failure at an abutment that included a pre-existing landslide have happened under flood conditions; a basic underlying cause of failure for each was probably the presence of a relatively easily erodible landslide. The three cases are (1) Cheurfas Dam, Algeria, which failed in 1885, (2) Euclides da Cunha Dam, Brazil, which failed in 1977, and (3) Star Mountain Dam, Oregon, United States, which failed in 1983.

- Cheurfas Dam—The right abutment of the original 37-m-high, masonry Cheurfas Dam in Algeria was in talus and alluvium (fig. 34) (Gignoux and Barbier, 1955). In 1885, a flood removed the right one-half of the dam, which was later rebuilt (see below). Cheurfas Dam has not been included in Appendix table A because I was unsuccessful in obtaining sufficient data on the original dam.

- Euclides da Cunha Dam—Euclides da Cunha Dam is a 92-m-high earthfill structure in southeastern Brazil. The original dam was completed in 1960 to provide hydroelectric power. "Ancient landslides," consisting of clayey talus, covered both abutments (Vargas, 1971; Brazilian Committee on Large Dams, 1982). Torrential rains in January 1977 generated a flood that quickly overtopped the dam, causing severe erosion of the right abutment and resulting failure of the dam. Almost all of the talus on the right abutment was removed by the force of the flood. Thus, when the dam was subsequently rebuilt, seepage was better controlled at that end of the dam than it was before the failure.

- Star Mountain Dam—The 1983 failure of 21-m-high Star Mountain Dam, an earthfill dam built in 1961 to provide local irrigation water to southeastern Oregon, is a similar case to that of the failure of Euclides da Cunha Dam. The entire right bank of Granite Creek at the damsite is the toe of a large pre-historic landslide. In late March 1983, a flood eroded out the original spillway, which was at the contact between the dam and the landslide abutment, causing damaging downstream flooding (Holton, 1983). The landslide character of the abutment probably was a factor in the failure of the spillway. When the dam was reconstructed, the

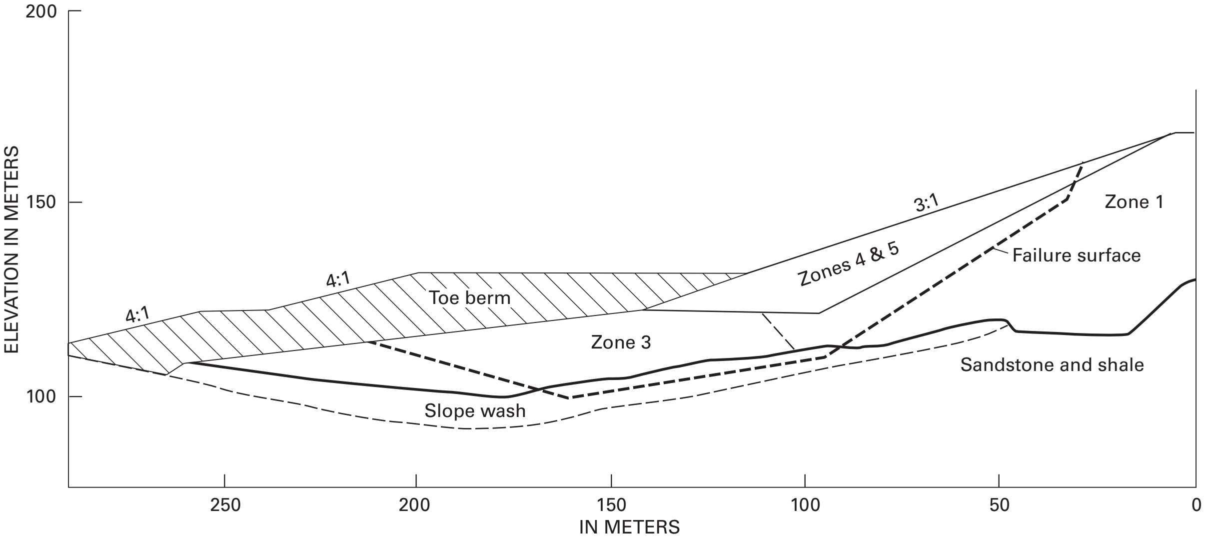


Figure 33. Cross section through B.F. Sisk (San Luis) Dam, California, United States, showing the location of the post-construction slide surface and the toe berm installed to stop further movement. The slide surface passed through slope wash and zones 1 and 3 of the dam. Modified from Von Thun (1985).

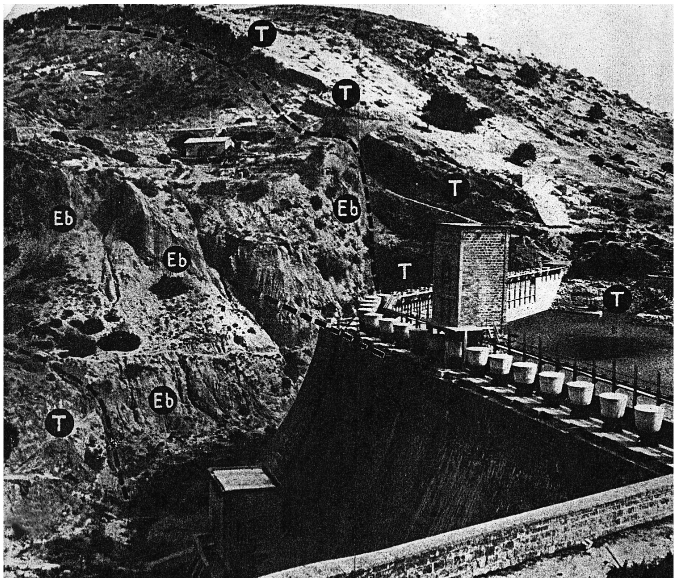


Figure 34. Cheurfas Dam, a masonry dam in Algeria. This dam was originally built in 1880–82, at a time when only very superficial geologic studies were made. As a result, the right abutment consisted of talus and alluvial debris. After the dam failed at its right end in 1885 due to a flood, it was rebuilt to a bedrock abutment slightly upstream, leaving a "dogleg" in the dam (Gignoux and Barbier, 1955, p. 208–209). Note: "Eb" is *éboulis,* which translates as "debris," or, in this case, talus and alluvium; "T" is limestone. Photograph by M. Gignoux, courtesy of Dunod/ Masson Sciences, Paris.

Figure 35. Star Mountain Dam, a 21-m-high irrigation dam in southeast Oregon, United States. The right abutment of this dam is the toe of a large landslide. After the dam failed in 1983 due to flood erosion of the unlined spillway at the landslide right abutment, a circular concrete-lined spillway was installed within the embankment. Photograph taken in 1998.

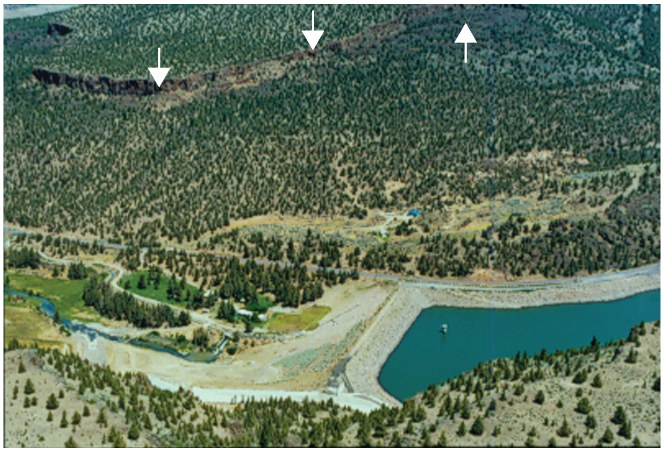


Figure 36. Oblique-aerial view of Ochoco Dam, central Oregon, United States, and the huge rock slide–lateral spread that serves as its right abutment. Note the long head scarp (marked by arrows) of the slide along the upper part of the ridge. Photograph taken in 1999 by U.S. Bureau of Reclamation.

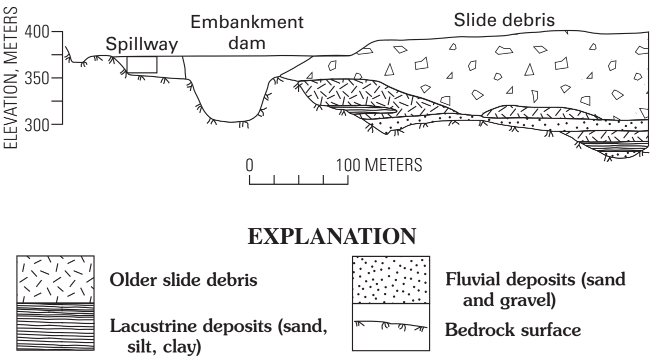
original surface spillway was replaced by a circular-concrete spillway embedded in the embankment (fig. 35).

Abutment and Foundation Seepage

Of the 254 dams in Appendix table A, 59 have had unanticipated seepage problems, most commonly through an abutment. Of these 59 cases, 51 are in the Western United States, a result of the large number of irrigation dams that were built in this area in the early part of the 20th century without adequate geologic exploration or foundation/abutment design. Another reason for the tabulation of so many Western U.S. dams that have reported seepage problems may be the readily available technical information on U.S. dams from State dam-safety agencies. Furthermore, it also is possible that seepage from non-U.S. dams has been underreported in the technical publications from which the data in Appendix table A were obtained.

- Ochoco Dam—Probably the most outstanding example of seepage through a landslide abutment of a Western United States irrigation dam is provided by Ochoco Dam, a 38-m-high hydraulic-fill dam built in 1920 in central Oregon. The right abutment and the foundation of the right end of this dam is a massive late Pleistocene rock slide–lateral spread (fig. 36) that probably resulted from plastic flow of bentonitic zones in dacitic tuff and tuffaceous claystone that underlay welded rhyolitic tuff of the slide mass (Carter, 1998a,b; Kunzer, 1998). Right-abutment seepage occurred during the first filling of the reservoir. Upstream right-abutment treatment in 1921 reduced this seepage from an estimated 100,000 m^3/day to 70,000 m^3/day. In 1950, additional modifications at the right end of the dam further reduced the seepage to approximately 25,000 m^3/day. Complete reconstruction of the right end of the dam and its immediate abutment during the 1990s has reduced seepage to acceptable levels.

- Howard Hanson Dam—Another Western U.S. example of seepage problems due to landslide material in an abutment is Howard Hanson Dam, a 72-m-high rockfill and earthfill flood-control dam that was built in 1962 in the Cascade Range of southwestern Washington. The right abutment for this dam is the toe of a large landslide in Tertiary andesite flows, andesitic tuffs, and breccias (fig. 37). The slide debris consists of a heterogeneous assemblage of rock blocks as large as 6 m in diameter in a matrix of finer debris (Galster, 1989a). After the first filling of the reservoir in 1965, a spring abruptly issued from the landslide materials about 100 m downstream from the right abutment. The spring originally flowed at about 450–550 m^3/day. Flow has since been controlled by a gravel blanket supported by a crib wall. A drainage adit was added in 1968. This system seems to adequately control abutment leakage through the slide debris.



Geology after Corps of Engineers unpublished data

Figure 37. Cross section through the site of Howard Hanson Dam in western Washington State, United States, showing the huge landslide that serves as the right abutment of the dam. Modified from Galster (1989a).

Mitigative Measures

Procedures used to prevent or alleviate problems encountered because of the existence of landslides at potential or actual damsites can be broadly subdivided into two main categories:

- Planning measures—These include those measures that avoid or alleviate the problems as part of the planning process (*passive* measures). Common measures are avoidance, dam-type selection, control of reservoir level, and/or relocation of the spillway.

- Physical prevention or remediation measures (*active* measures)—These commonly include removal of all or part of the landslide; flattening of the slope; construction of berms that serve as buttresses; and installation of impervious membranes or cutoffs, retaining walls, surface or underground drains, and rock-anchor systems. These physical prevention and remediation measures have been used in the abutments or foundations of 154 of the dams in Appendix table A. Seventy-seven of the 101 non-U.S. dams utilized active measures, as was the case for 77 of the 153 U.S. dams. As presented in Appendix table A, of the 154 dams that were subject to active prevention and remedial measures, the use of individual types of prevention and remediation are as follows (note, however, that multiple types have been used on many dams): partial removal of landslide deposits (46 dams), cutoff walls (43 dams), berms/buttresses (43 dams), grouting (36 dams), drainage (36 dams), impervious membranes/blankets (20 dams), flattening of abutment slopes (15 dams), rock anchors (12 dams), piles/piers (8 dams), guniting/dental work (six dams), retaining walls (5 dams), and other measures (6 dams). Another, sometimes overlooked, physical measure is the buttressing effect of the dam itself, which has proven to be a very important factor in the retention of many abutment landslides.

Planning Measures

Avoidance of Landslides

A very basic passive preventive measure if a landslide has been recognized in a planned foundation or abutment area during the siting process is *avoidance,* that is, relocation to a more favorable site nearby, or, in extreme cases, complete abandonment of the site.

Relocation of Site

Several cases have been noted in which a damsite was relocated because the original site included a hazardous landslide in the foundation or an abutment. Most of these dams have not been included in Appendix table A because as constructed they do not interact with landslides. Notable examples include the following:

- Orlik Dam—The most often cited example of relocation of a major dam because of a pre-existing landslide has been that of Orlik Dam on the Vltava River in the southwestern part of the Czech Republic (Záruba, 1965; Záruba and Mencl, 1976; Legget and Karrow, 1983; Legget and Hatheway, 1988). Preliminary studies for the siting of Orlik Dam indicated that a narrow stretch of the valley and the existence of Proterozic metamorphic rocks in the abutments would provide an ideal site for construction of a concrete-gravity dam. However, further study found that the narrowing of the valley at the site was actually caused by a massive Pleistocene rock slide. The original site was abandoned and a new site selected 200 m upstream, where the 91-m-high dam was successfully completed in 1963. For the same reason, several other potential damsites on the Vltava River have had to be relocated or abandoned.

- Salagou Dam—In the case of Salagou Dam on the Salagou River in south-central France, the site was relocated only a short distance away (Comité Français des Grandes Barrages, 1982). In addition to removing 87,600 m^3 of landslide material from the right abutment of the site and 38,450 m^3 from the left abutment, the 63-m-high earthfill dam was moved upstream—the right end a distance of 40 m and the left end 80 m—to avoid building on landslide materials. Construction was completed successfully in 1971.

- Kotmale Dam—Kotmale Dam, an 87-m-high rockfill dam on the Kotmale Oya (river) in Sri Lanka, was completed in 1985 to produce hydroelectric power. As construction began, a landslide was noted in the left abutment, necessitating relocation of the dam site 200 m downstream where it avoids any landslides (Kumara and Kulasinghe, 1987).

- Talbingo Dam—The original site for Talbingo Dam, a 161-m-high rockfill hydroelectric dam in the Snowy Mountains of southeastern Australia, included the toe of a large landslide of weathered basalt in the left abutment (Fell and others, 1992, p. 58). An alternative landslide-free site, more than 100 m upstream, was selected. The dam was completed in 1971, incorporating 2.3 million m^3 of the basaltic landslide deposit for its impervious core.

- North Fork Dam—An example of landslide avoidance during the original exploration stage of site selection is that of North Fork Dam, a hydroelectric dam on the Clackamas River in northern Oregon, United States. During site exploration for this 63-m-high concrete-arch dam, a 25–30 m thick deposit of slide and talus debris was noted in the left-abutment area (O'Reilly, 1958). As a result of this preliminary exploration, the dam was relocated upstream utilizing an abutment of stable basalt and was completed in 1958.

- Casitas and Castaic Dams—As indicated in Appendix table A, the axes of Casitas and Castaic Dams, California, United States, were realigned in the planning stage to minimize the effects of pre-existing landslides (Hanegan, 1973). In both cases, final alignment placed only a small part of the dam in contact with a landslide.

- San Dimas Dam—San Dimas Dam, California, was redesigned to reduce the area of contact of the dam with a pre-existing landslide.

There also have been a few cases in which one end of a pre-existing or partially built dam has been diverted to avoid a landslide, thus forming a "dogleg" in the dam. Three cases (not included in Appendix table A) where the axes of dams have been diverted midstream in order to avoid landslides are Cheurfas Dam (Algeria), Scott Dam (California, United States), and Gogoşu Dam (Romania).

- Cheurfas Dams—As briefly mentioned earlier, the original Cheurfas Dam (Cheurfas I) was a masonry dam built from 1880–82 at a time when only very superficial geologic studies were made of the damsite (Gignoux and Barbier, 1955, p. 63); for this reason the right end of the dam abutted against alluvium and talus deposits ("partially strengthened scree"). In 1885, a severe flood carried away the right one-half of the structure. By 1892, the dam had been rebuilt, leaving in place the left-end remnant that had survived the 1885 flood, but putting a "dogleg" in the dam to allow its right end to abut a stable limestone outcrop upstream from the unstable talus that formed the original right abutment (fig. 34) (Gignoux and Barbier, 1955; p. 63, 208; Walters, 1971, p. 313–320). During the early 1980s, it was decided to replace the 1892 dam because of siltation in the reservoir and the general instability of the site (Ajabi and others, 1991). The new dam (Cheurfas II) was built upstream at a more stable site.

Figure 38. Scott Dam on the Eel River, northern California, United States. During construction in 1921, the left end of this dam was diverted downstream to miss the landslide on the left bank of the river, resulting in a "dogleg" in the dam. Photograph taken in 1997 by J.C. Gamble, Pacific Gas and Electric Company, San Francisco.

- Scott Dam—Scott Dam (also known as Pillsbury Dam), a 42-m-high concrete-gravity structure on the Eel River in northwestern California, was built in 1921 to produce hydroelectric power. Construction began at the right end of the dam. When the dam was two thirds of the way across the river, it was realized that the planned left abutment was actually a "floater" of serpentinite in a slide of softened, weathered serpentinite and serpentine clay. The engineers in charge decided to divert the remainder of the dam downstream to miss the landslide, forming a "dog leg" (fig. 38) similar to that for Cheurfas Dam, which was described above (Kiersch and James, 1991; Goodman, 1993).

- Gogoşu Dam—Gogoşu Dam on the Danube River in Romania is a 24-m-high zoned earthfill dam that provides hydroelectric power to the nation. During construction, a slide occurred in the stiff, marly clays that formed the left abutment. In addition to partially removing the slide material, the left end of the dam axis was "upstream curved" to miss the slide area (Corda, 1988).

Site Abandonment

An option that can be considered in extreme cases is to abandon the damsite because the landslide problem at the chosen site is without a solution that is economically feasible, and because no suitable alternate site is available nearby. The literature search noted only two cases in which the original site was deemed completely unsuitable and was abandoned. These two cases are a site on the Romanche River in France and the Ok Ma tailings dam site in Papua New Guinea. Abandoned dam sites are not included in Appendix table A.

- Romanche River site—An apparently morphologically suitable site for a dam was located on the upper Romanche River in the French Alps (Gignoux and Barbier, 1955, p. 88; Záruba and Mencl, 1982, p. 238; Bowen, 1984, p. 311–312). The left abutment at this site was composed of stable granite and Triassic sandstones and limestones. The more moderately sloping right abutment also appeared to be stable. However, geologic investigation of the slope found that the entire right side of the valley at the site consisted of a landslide in Lias (Lower Jurassic) shales, which had constricted the valley, and overlay alluvial sandy gravels on the original valley floor (fig. 39). The site was abandoned.

- Ok Ma tailings dam site—The proposed Ok Ma ("ok" translates as "river") tailings dam was intended to provide a retention reservoir for tailings from the Ok Tedi gold/copper mine in the Star Mountains of western Papua New Guinea. However, in December 1983, during construction of this conventional zoned earthfill/rockfill dam, a major, deep-seated landslide occurred in the weak mudstones and siltstones of the middle Miocene Pnyang Formation at its proposed left abutment (Fookes and others, 1991; Fookes and Dale, 1992; Fookes and others, 2000). Because no technically or economically feasible option was available for mitigation of the landslide or for shifting the axis of the tailings dam to a position off the landslide, the tailings dam site was abandoned.

Redesign of Dams Because of Landslide Problems

A few dams have been redesigned when a landslide was discovered in the foundation or an abutment. Excellent examples are Selevir Dam in western Turkey and Sweasey Dam, California, United States.

- Selevir Dam—Selevir Dam is a 31-m-high earthfill, irrigation dam in western Turkey. During construction, movement occurred in schist that forms the right abutment. As a result, (1) the outlet tunnel was redesigned and rerouted, (2) the outlet portal excavation, which had caused the slide, was refilled with recompacted material (that is, the fill became a buttress berm), (3) the intake structure was moved 455 m upstream, and (4) the original cutoff trench was replaced by a concrete cutoff wall with piles extending to schist bedrock (Sezginer and Karacaoğlu, 1961).

- Sweasey Dam—Sweasey Dam, on the Mad River in northern California, was originally designed to be a 40–45 m high concrete arch municipal water-supply dam. During construction, however, a slide occurred in Franciscan Complex sandstones and clayey shales of the left abutment (Kiersch and James, 1991). As a

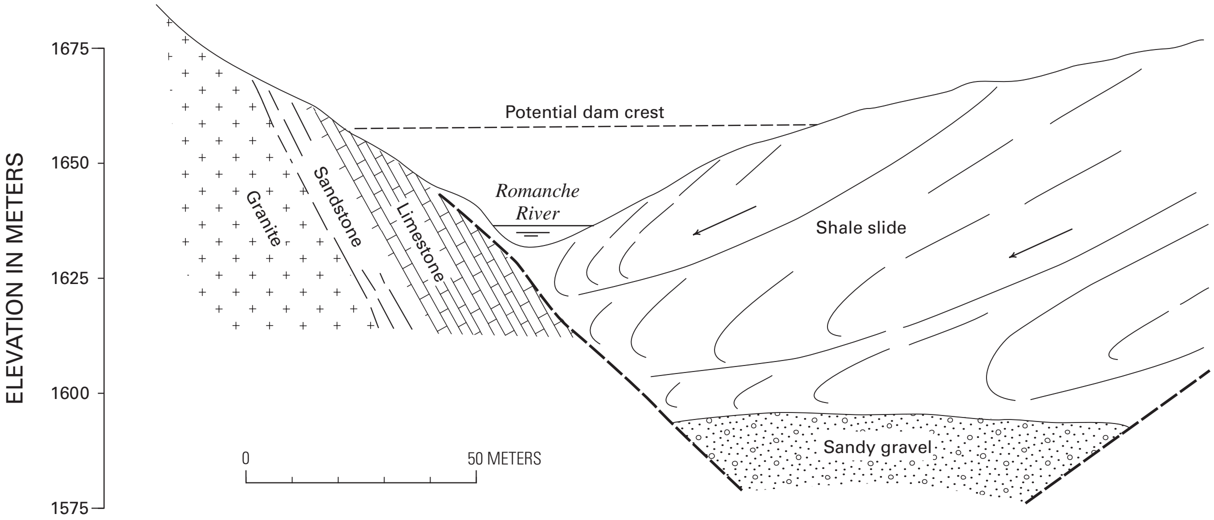


Figure 39. Cross section through a narrowed section of the Romanche River valley, France, showing the shale landslide that constricted the valley. Plans to construct a dam at this site were abandoned because of the landslide. Modified from Gignoux and Barbier (1955, p. 88).

result, the dam was redesigned from a full concrete arch to a composite section employing an arch dam across the channel section, which abutted a massive concrete thrust block at the left end. An earthfill section then connected the thrust block with the excavated left abutment. Design height was also reduced by 20 m to an as-constructed 23-m height. During the 1970s, the dam was purposely breached because of excessive sedimentation in the reservoir (no relation to the landslide).

As noted earlier, embankment dams are more flexible than concrete structures, and thus can be built on pre-existing landslides with less risk of stability problems than is the case for concrete, and particularly concrete-arch, structures. Three dams in Appendix table A that were changed from concrete to rockfill during the preliminary design process because of pre-existing landslides in their footprints are Iril-Emda Dam (Algeria), Kangaroo Creek (Australia), and Pandoh Dam (India).

Lowering Reservoir Level or Reducing Rate of Filling

Although use of these procedures tends to impair the function of the dam, they constitute an effective means of increasing abutment stability by reducing abutment pore pressures and reducing seepage through the abutment by lowering the head or reducing its rate of increase. Five cases of reservoir lowering or reduction of rate of filling have been noted in this study:

- Casanuova Dam (central Italy)—Filling of the reservoir was temporarily suspended pending installation of additional remedial measures (Catalano and others, 2000).
- Rossella Dam (Island of Sicily, Italy)—Reservoir level was lowered to counter reactivation of a left-abutment earthflow (Catalano and others, 2000).
- Los Naranjos Dam (Mexico)—Release from the reservoir was controlled as one of several mitigative measures to slow reactivation of a 2-million-m^3 slide in the right abutment (Ramirez Reynaga, 1998).
- Rio Grande Dam (Colorado, United States)—For several years in the 1990s, Rio Grande Dam (fig. 1) operated at lowered reservoir level mandated by the State of Colorado because of left-abutment seepage through the toe of a pre-existing rock slide. The problem was solved by installation of the following remedial measures at the left abutment: (1) retaining wall, (2) french drains, and (3) horizontal drains. After completion of the remedial measures, reservoir level was allowed to be raised.
- Sam's Valley Dam (Oregon, United States)—Operation at a temporarily lowered reservoir level has been mandated by the State of Oregon because of excessive seepage through the landslide right abutment.

Physical Measures for Foundation and Abutment Stabilization

Da Costa Nunes and others (1982) have noted several physical mitigative measures for stabilization of abutments that are threatened by landslides. These stabilization methods include removal of landslide deposits; flattening the abutment slope; construction of earthfill or rockfill berms that serve as buttresses; construction of cutoffs or keys, retaining walls, piles or caissons, and anchors; moving or reinforcing the spillway; guniting; and "dental work."

Removal of Landslide Deposits

For cases in which a decision has been made to proceed with construction of a dam at the site of an old landslide, removal of all or part of the landslide material has often been accomplished as a successful preventive measure. There are 47 cases in Appendix table A in which *part* of the landslide deposit has been removed, but the remainder is included in the foundation or as part of an abutment in contact with the dam. Some examples of dams from which all or part of the landslide deposit has been removed are briefly mentioned below. The dams for which the landslide deposit has been totally removed have not been included in Appendix table A.

Total Removal of Landslide

Examples of total removal of landslide material that would have interacted with a dam or its appurtenant structures include the following dams (not included in Appendix table A): Little Para (Australia) (Beal, 1975), Ouchi (Japan) (Mikuni, 1980; Watanabe, 1985), Bell Canyon (California, United States) (Connell and others, 1985), Los Vaqueros (California) (Simpson and Schmoll, 2001), Dillon (Colorado, United States) (Wahlstrom and Nichols, 1969), Kinzua (Pennsylvania, United States) (Philbrick, 1976), and Tioga (Pennsylvania, United States) (Wilshusen and Wilson, 1981). In most such cases, all or part of the removed material was used to construct a berm, which served as a buttress.

Partial Removal of Landslide

Removal of part of the landslide took place in 47 of the dams listed in Appendix table A; well-documented examples include Kangaroo Creek (Australia), Thomson (Australia), Gardiner (Canada), Slezka Harta (Czech Republic), Bort (France), Evinos (Greece), Kassa (Japan), Ouchi (Japan), d'Aït Youb (Morocco), Arenós (Spain), Cortes de Pallás (Spain), Broomhead (United Kingdom), Austrian (California, United States), Castaic (California), Hernandez (California), San Dimas (California), Black Lake No. 1 (Colorado, United States), and Silver Jack (Colorado).

Partial Removal of Talus Cover

Removal of part of talus cover from an abutment commonly consists of placing a wide cutoff trench through the talus into bedrock, but may involve stripping of a larger area to bedrock. There are 14 such cases in Appendix table A: Parangana (Australia) (fig. 22), Eberlaste (Austria), Gepatsch (Austria), Euclides de Cunha (Brazil), Serre-Ponçon (France), Ancipa (Italy), Ozola (Italy), Francisco Zarco (Mexico), Vicente Guerrero (Mexico), Wemmershoek (South Africa), Marmorera (Switzerland), Taylor Park (Colorado, United States) (fig. 4), Anderson Ranch (Idaho, United States), and Joes Valley (Utah, United States).

Partial Removal of Landslide Deposit Following Construction or Postconstruction Slope Failure

Partial removal of landslide materials during construction or postconstruction slope failure took place at 65 of the dams in Appendix table A; examples of these include Quebrada de Ullum (Argentina), Gardiner (Canada), Slezska Harta (Czech Republic), Daniel Palacios (Ecuador), Chaudanne (France), Los Naranjos (Mexico), Tresna (Poland), Arenós (Spain), Broomhead (United Kingdom), Castaic (California, United States), Trinity (California), Ridgway (Colorado, United States), Silver Jack (Colorado), Lovewell (Kansas, United States), Agate (Oregon, United States), Lookout Point (Oregon), Oahe (South Dakota, United States), Joes Valley (Utah, United States), and Grand Coulee (Washington, United States).

Flattening Abutment Slopes

Flattening of abutment slopes (unloading the upper part of the landslide) has been used as a preventive/remedial measure on 15 of the dams listed in Appendix table A. These are Quebrada de Ullum (Argentina), Gardiner (Canada), Dalešice (Czech Republic), Nechranice (Czech Republic), Slezska Harta (Czech Republic), Ranaptrap Sagar (India), Los Naranjos (Mexico), Cortes de Pallás (Spain), Devil's Dingle (United Kingdom), Castaic (California, United States), San Dimas (California, United States), Silver Jack (Colorado, United States), Agate (Oregon, United States), Oahe (South Dakota, United States), and Grand Coulee (Washington, United States).

Earthfill or Rockfill Berms Serving as Buttresses

Earthfill and rockfill berms often have been used as buttresses to increase the stability of abutment slopes. If these berms include fine-grained materials, they may also reduce seepage at the toe of the dam. In many cases, the material for construction of berms is obtained directly from landslide deposits excavated from upslope areas along or near the abutment. Thirty-nine examples of construction of berms as abutment-slope buttresses are presented in Appendix table A. Some of the more interesting examples and the types of berms installed include the following:

- Thomson Dam (Australia)—2.6-million-m^3 rockfill berm
- Eberlaste Dam (Austria)—50-m-wide stabilizing fill that served as berm
- Dalešice Dam (Czech Republic) (fig. 10)—150,000-m^3 rockfill berm
- Mornos Dam (Greece)—8-million-m^3 toe berm placed along the reservoir shore immediately upstream from dam
- Tablachaca Dam (Peru)—467,000-m^3 toe berm placed in the reservoir immediately upstream from dam 10 years after original construction
- Liptovaská Mara Dam (Slovakia)—700,000-m^3 sand/gravel berm
- Cortes de Pallás Dam (Spain)—800,000 m^3 excavated from upper part of slide and moved to lower part to form toe berm

Figure 40. Oblique view of the left end of Mojave River Dam, an earthfill flood-control structure in southern California, United States, showing the two earth berms that were added to the left abutment to buttress a small abutment slide (marked by arrow) that occurred during construction. Photograph taken in 1998.

- B.F. Sisk (San Luis) Dam (California, United States)—Addition of an upstream toe berm (fig. 32) was necessitated by a postconstruction slide in left abutment
- Mojave River Dam (California, United States)—Two earthfill berms serve as buttresses (fig. 40)
- Terminal Dam (California, United States)—6.5-m-high upstream and downstream berms
- Silver Jack Dam (Colorado, United States)—87,000-m^3 toe berm obtained from slope above abutment
- Lake Harriet Dam (Oregon, United States)—Berm with an impervious bentonitic membrane was placed against upstream face of the concrete-arch dam, mainly to reduce seepage (fig. 14)
- Oahe Dam (South Dakota, United States)—3.5-million-m^3 construction-caused slide in left abutment was excavated and material was placed as a berm that serves as toe buttress

Dam Serving as Buttress

Often, potential abutment slides have been successfully buttressed by the mass of the dam itself. In this manner, the abutment slopes may be more stable than before the dam was built. However, the existence of the dam will have little effect on seepage through the abutment. All dams have a buttressing effect; some examples from Appendix table A, where this effect has been specifically noted, include Iril-Emda (Algeria), Mornos (Greece), Pandoh (India), Clyde (New Zealand), Trinity (California, United States), Gross (Colorado, United States) (figs. 5 and 6), Ridgway (Colorado), Lovewell (Kansas, United States), Conchas (New Mexico, United States), Oahe (South Dakota, United States), Calder (Utah, United States), Jordanelle (Utah), Red Creek (Utah), and Yale (Washington, United States).

Cutoffs or Keys

An impervious cutoff (usually concrete) is often placed in a trench that is excavated beneath the location of the dam core. The main function of a cutoff usually is to reduce seepage through the foundation or abutment. However, these cutoffs also “key” the dam into the foundation or abutment, and thus increase stability in addition to reducing permeability. Some examples of dams with cutoffs are given in the following section on reducing seepage.

An instance of the reinforcement of a landslide abutment using a concrete mass is San Jacinto Dam (Bolivia), where the left abutment was strengthened by filling adits with concrete (Riemer, 1995).

Retaining Walls

Conventional retaining structures occasionally have been used to increase abutment stability during construction. These walls commonly are left in place and become part of the dam. Dams in Appendix table A in which retaining walls were used to increase abutment stability include Zardezas (Algeria), Ichari (India), Jaldhaka Stage I (India), Ranaptrap Sagar (India), Tresna (Poland), Brooktrails No. 3 North (California, United States), Rio Grande (Colorado, United States) (fig. 1), Conchas (New Mexico, United States), and Grand Coulee (Washington, United States) (fig. 21).

Piles and Caissons

Dams from Appendix table A in which piles or caissons have been used to increase lateral stability include Wuping (China, vertical rock piles), Pong (India, concrete caissons), Bass Lake (Montana, United States, sheet piling), Madison (Montana, steel piling), Swift (Washington, United States, sheetpiling), and McElroy’s Run (West Virginia, United States, augercast grout columns).

Anchors

Anchors (usually prestressed steel) are often used to increase the stability of rock abutments, particularly during construction. Included in Appendix table A are the following dams that have successfully utilized anchors in abutments: Meishan (China), Dalešice (Czech Republic) (fig. 10), Daniel Palacios (Ecuador), Chaudanne (France), Ranaptrap (India), Kawamata (Japan), Santa Rosa (Mexico), Tablachaca (Peru), Tresna (Poland), Pacoima (California, United States), and San Dimas (California).

Moving or Reinforcing Spillway

In a few cases, either the main or the emergency spillway has been known to leak water into or cause erosion of a landslide abutment. In these cases, the spillway has either been moved to the other end of the dam or has been sealed or reinforced to prevent leakage or erosion. Examples of such cases in Appendix table A include the following:

- Trinità Dam (Island of Sicily, Italy)—The spillway, which was located on a pre-existing earth flow–earth slide, was founded on a system of piles to protect it from movement (Catalano and others, 2000).

- Austrian Dam (California, United States)—The spillway was relocated (partially to protect the spillway and partially to help stabilize the landslide abutment).

- Star Mountain Dam (Oregon, United States)—A circular concrete-lined emergency spillway replaced an earlier unlined spillway that had failed due to flood erosion, thus causing failure of the landslide abutment, and then failure of the dam (fig. 35).

Guniting

Although guniting provides almost no direct structural strength, it is occasionally used to increase the stability of a very steep slope by inhibiting surface erosion. The only dams in Appendix table A with abutment slopes that are protected by gunite are Santa Rosa (Mexico) and Pacoima (California, United States).

"Dental Work"

"Dental work" is the filling of joints and other voids with cement grout or concrete to increase local stability and possibly to reduce permeability. It is often used on rock abutments during construction. The only Appendix table A dams for which dental work has been carried out on a rock abutment to reduce the landslide hazard during excavation are Tooma (Australia), Daule Peripa, (Ecuador), Los Naranjos (Mexico), and Jordanelle (Utah, United States).

Physical Measures for Reducing Abutment and Foundation Seepage

Impervious Cutoffs

Probably the most common seepage-reduction measures are impervious cutoffs that are constructed through the landslide materials to solid rock. Usually, these cutoffs are made of Portland-cement concrete and serve as vertical "keys" in zone 1 of the dams to increase stability of the structure in addition to reducing seepage; however, some are impervious-soil or bentonitic-slurry cutoffs, which do little or nothing to increase stability. Cutoffs are commonly installed during the construction process. Dams in which concrete cutoffs have been installed during construction to prevent seepage include O'Shannassay (Australia), Eberlaste (Austria, asphaltic concrete), Freibach (Austria), Ichari (India), Pandoh (India), Salal (India), Ancipa (Italy), Ozola (Italy), Pian Palù (Italy), Vodo (Italy), Rules (Spain), Marmorera (Switzerland), Selevir (Turkey), and Woodhead No. 2 (United Kingdom). Flexible slurry-trench or clay cutoffs were installed at Eberlaste Dam (Austria, slurry trench), Euclides da Cunha (Brazil, "impervious soil"), Nechranice (Czech Republic, "clay-cement"), Francisco Zarco Dam (Mexico, slurry trench), and Vicente Guerrero (Mexico, impervious clay). Cases in which a cutoff was added when seepage problems were encountered during operation include Site 19 (New York, United States), Long Park (Utah, United States), and Mud Mountain (Washington, United States).

Impervious Curtains, Membranes, and Blankets

Seepage can also be intercepted and diverted by impervious curtains, membranes, or blankets that have little inherent structural strength, for example, cement or chemical grout curtains, plastic or geosynthetic membranes, and clay blankets. Thirty-seven dams from Appendix table A include grout curtains in their foundations and/or abutments. Fourteen of the dams in Appendix table A include impervious membranes or clay blankets. These measures are not intended to act as strengthening "keys" through the landslide material to bedrock, but may increase stability as well as reduce seepage by locally lowering pore pressures in the foundation and abutments. Dams in which these measures have been used include the following:

- Grouting (during construction)—Quebrada de Ullum (Argentina), Parangana (Australia), Tooma (Australia), Durlassboden (Austria), Euclides da Cunha (Brazil), Polemidhia (Cyprus), Terlicko (Czechoslovakia), Chaudanne (France), Ranaptrap Sagar (India), Salal (India), Beauregard (Italy), Kassa (Japan), Terayama (Japan), Francisco Zarco (Mexico), Marmorera (Switzerland), Castaic (California, United States), San Dimas (California), Black Lake No. 1 (Colorado, United States), El Vado (New Mexico, United States), and Moon Lake (Utah, United States)

- Grouting (after seepage or movement developed)—Freibach (Austria), Yeso (Chile), Meishan (China), Los Naranjos (Mexico), Nakhla (Morocco), Arnensee (Switzerland), Broomhead (United Kingdom), Austrian (California, United States), Pacoima (California), Clear Lake (Colorado, United States), Scholl (Colorado), Young's Creek Nos. 1 and 2 (Colorado), Bull Run No. 2 (Oregon, United States), and Waterbury (Vermont, United States)

- Impervious membranes or clay blankets (during construction)—Seymour Falls (Canada), Ranaptrap Sagar (India), Salal (India), Terayama (Japan), and South Creek (Utah, United States)

- Impervious membranes or clay blankets (after seepage or movement had occurred)—Meishan (China), Beaver (Colorado, United States), Cedar Mesa (Colorado), Matheson (Colorado), Scholl (Colorado), Young's Creek Nos. 1 and 2 (Colorado), Black Lake (Montana, United States), Hyalite (Montana), and Stemilt Main (Washington, USA)

Note the relatively large number of dams in the Western United States that have been repaired by installation of grout curtains or impervious membranes after the occurrence of seepage. This is indicative of the seriousness of seepage problems faced by dams that have been built on landslides.

Drainage Systems

Drainage systems are commonly used to intercept water before it enters the landslide deposit or to remove water from the landslide material. Drainage helps to stabilize abutment landslide materials, to control seepage through the abutment or foundation, and to reduce the possibility of piping. Thirty-four dams in Appendix table A have been improved by installation of drainage systems. These systems commonly consist of one or more of the following: surface drainage, interceptor trench drains (vertical trenches backfilled with pervious materials, such as sand and gravel), "horizontal" drains, adits and galleries, filter blankets, and pumping wells. Toe drains and relief wells also are used to allow water to exit without building up pore pressures within the abutment or foundation materials. Any of these measures may be installed during dam construction as preventive measures, or may be added later as remedial measures.

Examples of dams in Appendix table A for which drainage systems were added either during or after construction include the following:

- Surface drains—Slezska Harta (Czech Republic), Polyphyton (Greece), Wemmershoek (South Africa), Currier #2 (Colorado, United States), Silver Jack (Colorado), and Nevada Creek (Montana, United States)

- Trench drains—Broomhead (United Kingdom), Brooktrails No. 3 North (California, United States), Kiser Slough (Colorado, United States), Rio Grande (Colorado), and Bumping Lake (Washington, United States)

- Horizontal drains—Pandoh (India), Tablachaca (Peru), Rio Grande (Colorado, United States), Silver Jack (Colorado), South Creek (Utah, United States), and Howard Hanson (Washington, United States)

- Adits, tunnels, and galleries—Polyphyton (Greece), Nakhla (Morocco), Tablachaca (Peru), City of Portland No. 3 (Oregon, United States), and Howard Hanson (Washington, United States)

- Filter blankets—Wungong (Australia) and Howard Hansen (Washington, United States)

- Pumping wells—Evinos (Greece)

- Toe drains and relief wells—Quebrada de Ullum (Argentina), Engenheiro Avidos (Brazil), saddle dam for F. Mohamed B.A. el Khattabi (Morocco), Jones #2 (Colorado, United States), Overland #1 (Colorado), and Howard Hanson (Washington, United States)

Multiple Mitigation Methods

All of the above preventive and remedial measures have been known to increase stability and/or reduce seepage, and, in some cases, they have been completely successful. However, in most successful cases more than one method has been utilized.

Figure 41. The remains of Mystic Lake Dam, a small water-supply dam in southwestern Montana, United States, which was constructed in 1903–04 on the site of a landslide dam. The earthfill dam was purposely breached in 1984 because of the hazard it posed to the downstream city of Bozeman. Photograph taken in 1997.

Breaching as a "Remedy"

The only dams that I know of that have been purposely breached because of the downstream hazard that they posed due to a landslide are Mystic Lake Dam, a 13-m-high, earthfill water-supply dam for the city of Bozeman, Montana, United States, and Site 19 Dam, a 20-m-high flood-control dam in New York State, United States.

- Mystic Lake Dam—Mystic Lake Dam (fig. 41), which was constructed in 1903–04 on the site of a "recent" (about 100 yr old) landslide dam, leaked excessively throughout its lifetime, and was in possible danger of failure due to piping. Thus, it was purposely breached in 1984 in response to the U.S. Dam Safety Program (High Country Independent Press, 1985).

- Site 19 Dam—Site 19 Dam, which was constructed in 1971, was breached in 1980 because of excessive leakage in the left abutment due to a pre-existing ancient slump (Kirkaldie and Thomas, 1984; Kiersch and James, 1991). The dam was redesigned and rebuilt with remedial measures consisting of (1) a cutoff trench to bedrock and into the embankment and (2) an enlarged foundation drainage system.

Summary and Conclusions

Geologists sometimes feel that it is impossible to safely construct a dam on a pre-existing landslide. Conversely, some engineers have been known to assume that today's advanced construction and prevention techniques can overcome any landslide problem. This study of 254 dams that either have been built on pre-existing landslides or were subjected to landslides during or after construction shows that reality is somewhere in between these extremes. Some dams have been built on landslides with no ensuing difficulties, even in cases where preventive measures were not used; others have encountered serious seepage or stability problems, most of which have been at least partly alleviated by installation of remedial measures, such as berms, cutoff walls, drainage systems, grouting, or impervious membranes. However, *avoidance* of sites where landslides may result in exorbitant costs during construction or remediation should always be considered as a serious option.

This study has noted many cases in which dams built on landslides have operated for many years without major stability or seepage problems. In only four cases, Cheurfas Dam (Algeria) [not included in Appendix table A], Euclides da Cunha Dam (Brazil), St. Francis Dam (California, United States), and Star Mountain Dam (Oregon, United States), can failure (that is, natural breaching) of a dam be considered to have been related to problems caused by pre-existing landslides. Only in the case of the failure of St. Francis Dam was the failure catastrophic in terms of loss of life. Mystic Lake Dam (fig. 39) and Site 19 Dam were the only cases found in which a dam was intentionally breached because of concerns that major landslide-related failure was probable.

This survey indicates that seepage through an abutment has been the most common negative result of building a dam on a landslide. Seepage occurs through open joints and failure surfaces in rock and earth landslides, and through voids in more pervious landslide masses, such as rock falls and debris flows. When carried to the extreme, seepage could possibly lead to piping (particularly in loose granular materials) and possible dam failure; however, we found no case in which this has occurred as a result of a dam having been constructed on a landslide. More commonly, seepage has resulted in loss of water intended for irrigation or power production, thus resulting in project inefficiency and economic loss.

There seems to be no clear indication as to which landslide types perform best or worst when used as an abutment or a foundation. In most cases, all landslide types have proven to be fairly stable, although slides in shales appear to perform the poorest. In contrast, all landslide types seem to be subject to possible seepage problems unless proper preventive or remedial measures are taken. In general, rock-fall deposits (such as talus) are pervious, and thus provide ready paths for seepage; however, some talus deposits include enough fine material to be relatively impervious. Thus, in regard to both stability and seepage, the physical characteristics of the individual landslides and the physical properties of the landslide materials should be carefully considered in the siting process for any dam in which a landslide will be part of an abutment or the foundation. Of particular importance in regard to seepage is the permeability of the landslide mass.

Acknowledgments

I would like to thank my many professional colleagues around the world who helped me by providing ideas and case histories for this study.

In the United States, special thanks go to the various State dam-safety agencies and Federal dam-building and dam-regulating agencies, who allowed ready access to their files on dams that have been built on landslides. The same degree of cooperation was extended by companies, irrigation districts, city water departments, and private parties, who own the dams.

Thanks also go to CAMBIOR (Canada) and Geotecnica Consultores (Chile), who provided funding for the early stages of the study, an expenditure that ensured its success.

I would also like to note the day-to-day help I received from colleagues in the U.S. Geological Survey, the U.S. Bureau of Reclamation, and the U.S. Army Corps of Engineers, as well as the services of the excellent technical libraries of these agencies.

References Cited

Agnew, A.F., 1985, Dissecting a dam: Bulletin of the Association of Engineering Geologists, v. 22, no. 4, p. 458.

Ajabi, A., Amrane, K, and Ezzitouni, M., 1991, Cheurfas II – construction d'un barrage-poids en béton conventionnel sur foundations médiocres, *in* Transactions: 17th International Congress on Large Dams, International Commission on Large Dams, Vienna, June 17–21, v. 3, p. 1,313–1,339.

Alberro, J., 1976, Filtrations in the foundations of Santa Rosa Dam, *in* Transactions: 12th International Congress on Large Dams, International Commission on Large Dams, Mexico City, March–April, v. 2, p. 299–311.

Alonso, E.E., Gens, A., and Lloret, A., 1993, The landslide of Cortes de Pallas, Spain: Géotechnique, v. 43, no. 4, p. 507–521.

Amundson, C.T., and Scofield, D.H., 1998, Engineering geology of Elk Creek Dam, Jackson County, Oregon, *in* Burns, S., ed., Environmental, groundwater and engineering geology—applications from Oregon: Belmont, Calif., Star Publishing Company, p. 133–142.

Anderson, J.G.C., and Trigg, C.F., 1976, Case histories in engineering geology: London, Elek Science, 204 p.

ANIDEL, 1952, Dams for hydroelectric power in Italy: Associazione Nazionale Imprese Produttrici e Distributrici di Energia Elettrica, Rome, v. 2, 272 p. plus figures, v. 4, 302 p. plus figures, v. 5, 234 p. plus figures.

ANIDEL, 1953, Dams for hydroelectric power in Italy: Associazione Nazionale Imprese Produttrici e Distributrici di Energia Elettrica, Rome, v. 3, 253 p. plus figures, v. 6, 271 p. plus figures, v. 7, 257 p. plus figures.

ANIDEL, 1961, Dams for hydroelectric power in Italy: Associazione Nazionale Imprese Produttrici e Distributrici di Energia Elettrica, Rome, v. 1, 959 p.

Andreu, F.J., Martinez-Alegria, R., and Utrillas, J.L., 1988, Analisis de estabilidad y estudio de reacondicionamiento de una ladera en la margen izquierda del Rio Mijares (Castellon), *in* Proceedings: 2d Simposio sobre Taludes y Laderas Inestables, Andorra la Vella, March, p. 295–309.

Atwood, W.W., 1918, Relation of landslides and glacial deposits to reservoir sites: U.S. Geological Survey Bulletin 685, 38 p.

Atwood, W.W., and Mather, K.F., 1932, Physiography and Quaternary geology of the San Juan Mountains, Colorado: U.S. Geological Survey Professional Paper 166, 176 p.

Austrian National Committee on Large Dams, 1991, Dams in Austria: Vienna, 331 p.

Barbier, R., 1974, La géologie au service des grands travaux, *in* Proceedings: Colloquim, Géologie de L'Ingénieur, Société Géologique de Belgique, Liége, September, p. 77–111.

Barclay, C.S.V., 1968, Geology of the Gore Canyon-Kremmling Area, Grand County, Colorado: U.S. Geological Survey Open-File Report, 187 p.

Baum, R.L., and Odum, J.K., 1996, Geologic map of slump-block deposits in part of Grand Mesa area, Delta and Mesa Counties, Colorado: U.S. Geological Survey Open-File Report 96-017, 12 p. plus map, scale 1:24,000.

Baum, R.L., and Odum, J.K., 2003, Retrogressive slumping at Grand Mesa, Colorado, *in* Boyer, D.D., Santi, P.M., and Rogers, W.P., eds., Engineering geology in Colorado—contributions, trends, and case histories: Association of Engineering Geologists Special Publication 14 and Colorado Geological Survey Special Publication (CD-ROM).

Beaulieu, J.J.D., 1974, Geologic hazards of the Bull Run Watershed, Multnomah and Clackamas Counties, Oregon: Oregon Department of Geology and Mineral Industries Bulletin 82, 77 p.

Beal, J.C., 1975, Engineering geology of the Little Para damsite, *in* Proceedings: 2d Australia-New Zealand Conference on Geomechanics, Brisbane, July 21–25, p. 207–212.

Beene, R.R.W., 1967, Waco Dam slide: Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers, v. 93, no. SM4, July, p. 35–44.

Benson, S., and Pate, K., 1998, Dams of the Lower Deschutes River—Round Butte, Pelton Arch, and Pelton Regulating Dams, *in* Burns, S., ed., Environmental, groundwater, and engineering geology—applications from Oregon: Belmont, Calif., Star Publishing Company, p. 45–58.

Bernton, H., 2000, Mount St. Helens debris still sullies Toutle River: Portland, Oreg., The Oregonian, 16 January.

Bhatnagar, P.S., and Parkash, V.A., 1967, Stability of excavated slopes around intake areas—Beas Dam at Pong, India, *in* Transactions: 9th International Congress on Large Dams, International Commission on Large Dams, Istanbul, September 4–8, v. 1, p. 1,051–1,067.

Bliton, W.S., 1989, Lewis River projects, *in* Galster, R.W., ed., Engineering geology in Washington: Washington Division of Geology and Earth Resources, v. 1, p. 277–298.

Bock, R.W., and Harber, W.G., 1974, Problems encountered in construction of dam foundations, *in* Foundations for dams: Proceedings, Engineering Foundation Conference, sponsored by the Geotechnical Engineering Division, American Society of Civil Engineers, and U.S. Committee on Large Dams, Asilomar, Calif., March, p. 87–113.

Bosler, J.C., Gratwick, C., Beattie, N., and Maso, S., 1991, Earthfill dam on a foundation of fissured clay containing an old slide surface, *in* Transactions: 17th International Congress on Large Dams, International Commission on Large Dams, Vienna, June 17–21, v. 3, p. 1,555–1,575.

Boufous, L., and Benzekri, J., 1985, Étude des problèmes d'infiltration a l'aval de la digue F du barrage De Mohamed Ben Abdelkrim el Khattabi sur L'Oued Neckor, *in* Transactions: 15th International Congress on Large Dams, International Commission on Large Dams, Lausanne, v. 3, p. 947–963.

Bowen, R., 1984, Geology in engineering: London, Elsevier Applied Science Publishers, 411 p.

Bravo, G., 1967, La fondation du barrage de Iznajar, *in* Transactions: 9th International Congress on Large Dams, International Commission on Large Dams, Istanbul, September 4–8, v. 1, p. 573–582.

Brazilian Committee on Large Dams, 1982, Technical data about Euclides da Cunha Dam, *in* ICOLD Publications Committee, eds., Main Brazilian dams—design, construction and performance: published for 14th International Congress on Large Dams, International Commission on Large Dams, Rio de Janeiro, p. 411–435.

Brink, A.B.A., 1981, Engineering geology of Southern Africa: Pretoria, Building Publications, v. 2, 255 p.

Bromehead, C.E.N., 1936, Geology of reservoir-damsites, *in* Transactions: 2nd International Congress on Large Dams, International Commission on Large Dams, Washington, D.C., v. 4, p. 113–119.

Brown, R., Gillon, M., and Deere, D., 1993, Landslide stabilization at the Clyde Power Project, New Zealand, *in* Anderson, L.R., ed., Geotechnical practice in dam rehabilitation: American Society of Civil Engineers Geotechnical Special Publication 35, p. 299–319.

Bryant, B., 1990, Geologic map of the Salt Lake City 30′×60′ quadrangle, north-central, Utah, and Uinta County, Wyoming: U.S. Geological Survey Miscellaneous Investigations Map I-1944, scale 1:100,000.

Bujak, M., Glab, W., Moraczewski, K., and Wolski, W., 1967, Preventive measures against the rock slide at Tresna Dam site, *in* Transactions: 9th International Congress on Large Dams, International Commission on Large Dams, Istanbul, September 4–8, v. 1, p. 1,027–1,036.

Burwell, E.B., Jr., and Moneymaker, B.C., 1950, Geology in dam construction, *in* Paige, S., ed., Application of geology to engineering practice—Berkey Volume: Geological Society of America, p. 11–43.

Bzioui, M., and Chraibi, A.F., 1991, Barrage d'Aït Youb adaptation du projet aux conditions géologiques réelles de la fondation, *in* Transactions: 17th International Congress on Large Dams, International Commission on Large Dams, Vienna, June 17–21, v. 3, p. 601–612.

Cabanius, J., and Maigre, R., 1958, The Durance development—the Serre-Ponçon dam—Travaux: 6th International Congress on Large Dams, International Commission on Large Dams, August, no. 286, p. 43–60.

Carrara, P.E., 1990, Surficial geologic map of Glacier National Park, Montana: U.S. Geological Survey Miscellaneous Investigations Series Map I-1508-D, scale 1:100,000.

Carter, B.H., 1998a, Ochoco Dam, Crook County, central Oregon, *in* Burns, S., ed., Environmental, groundwater and engineering geology—applications from Oregon: Belmont, Calif., Star Publishing Company, p. 59–67.

Carter, B.H., 1998b, Safety of dams modifications to Ochoco Dam, Crooked River project, Oregon, *in* Proceedings: 33rd Symposium on Engineering Geology and Soils Engineering, Reno, Nev., March, p. 25–36.

Castelucci, P., Coli, M., and Lazzeri, D., 1999, Studio geostrutturale–geomeccanico dell spalla destra della diga di Riolunato (Appennino Modenese): Geologia e Geotecnica Ambientale, v. 36, no. 2-3, p. 99–105.

Castilla, J.E., and Colina, P., 1985, Santa Rosa arch dam, reinforcement of the left bank, *in* Transactions: 15th International Congress on Large Dams, International Commission on Large Dams, Lausanne, June 24–28, v. 4, p. 843–862.

Castro, F., and Garces, E., 1985, Cement-bentonite cutoff for reconditioning Bullileo earth dam, *in* Transactions: 15th International Congress on Large Dams, International Commission on Large Dams, Lausanne, June 24–28, v. 4, p. 619–632.

Catalano, A., Chieppa, V., and Russo, C., 2000, Interaction between dams and landslides—three case histories, *in* Bromhead, E., Dixon, N., and Ibsen, M-L., eds., Landslides in research, theory and practice: London, Thomas Telford, Proceedings, 8th International Symposium on Landslides, Cardiff, Wales, June 26–30, v. 1, p. 227–232.

Cavallin, J.E., 1991, Terminal Dam, design and construction of an earthfill dam on a soft foundation, *in* Transactions: 17th International Congress on Large Dams, International Commission on Large Dams, Vienna, June 17–21, v. 3, p. 1,179–1,198.

Central Board of Irrigation and Power, 1979, Beas Dam at Pong, *in* Design and construction features of selected dams in India: Indian National Commission of the International Commission on Large Dams, New Delhi, Publication 138, p. 183–235.

Chandler, R.J., 1976, The history and stability of two Lias clay slopes in the upper Gwash valley, Rutland: Philosophical Transactions Royal Society of London, series A, v. 283, p. 463–491.

Chatterjee, B., 1979, Geotechnical problems in planning and execution of an hydro-electric project in Darjeeling Himalaya: International Association of Engineering Geology Bulletin, no. 20, p. 73–77.

Chen, L., Zhang, T., Lin, T., Zhou, X., and Chen, Z., 2001, Consolidation and stability behavior of a high rockfill dam built on soft clay foundation, *in* Proceedings: 3rd International Conference on Soft Soil Engineering, Hong Kong, December, p. 175–180.

Chinese National Committee on Large Dams, eds., 1987, Large dams in China—history, achievement, prospect: Beijing, China Water Resources and Electric Power Press, 249 p.

Cifres, E., 1998, New spillway for 105 m high rockfill dam, in order to update hydrologic and geotechnical safety—case of Arenós Dam, Spain, *in* Berga, L., ed., Dam safety: Proceedings, International Symposium on New Trends and Guidelines on Dam Safety, Barcelona, June 17–19, v. 2, p. 1,379–1,386.

Clarke, D.D., 1904, A phenomenal landslide: American Society of Civil Engineers Transactions, v. 53, no. 984, p. 321–412.

Colton, R.B., Holligan, J.A., and Anderson, L.W., 1975a, Preliminary map of landslide deposits, Durango 1°×2° quadrangle, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-703, scale 1:250,000.

Colton, R.B., Holligan, J.A., and Anderson, L.W., 1975b, Preliminary map of landslide deposits, Greeley 1°×2° quadrangle, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-704, scale 1:250,000.

Colton, R.B., Holligan, J.A., Anderson, L.W., and Patterson, P.E., 1975c, Preliminary map of landslide deposits, Leadville 1°×2° quadrangle, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-701, scale 1:250,000.

Colton, R.B., Holligan, J.A., Anderson, L.W., and Shaver, K.C., 1975d, Preliminary map of landslide deposits, Moab 1°×2° quadrangle, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-698, scale 1:250,000.

Colton, R.B., Holligan, J.A., Anderson, L.W., and Whitney, J.W., 1975e, Preliminary map of landslide deposits, Grand Junction 1°×2° quadrangle, Colorado and Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-697, scale 1:250,000.

Colton, R.B., Holligan, J.A., Patterson, P.E., and Anderson, L.W., 1975f, Preliminary map of landslide deposits, Craig 1°x2° quadrangle, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF 700, scale 1:250,000.

Colton, R.B., Patterson, P.E., Holligan, J.A., and Anderson, L.W., 1975g, Preliminary map of landslide deposits, Montrose 1°×2° quadrangle, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-702, scale 1:250,000.

Comité Español de Grandes Presas, 1993, Arenós, *in* Selección de presas Españolas, 1973–1993: Ministerio de Obras Públicas, Transportes y Medio Ambiente, Madrid, p. 72–79.

Comité Français des Grandes Barrages, 1982, La reconnaissance des sites de barrage difficultés rencontrées, *in* Transactions: 14th International Congress on Large Dams, International Commission on Large Dams, Rio de Janeiro, May 3–7, v. 2, p. 877–891.

Comité National Suisse des Grandes Barrages, 1976, Rapport de synthèse, *in* Transactions: 15th International Congress on Large Dams, International Commission on Large Dams, Mexico City, March 29–April 2, v. 4, p. 495–532.

Committee on Failures and Accidents to Large Dams, 1976, Lessons from dam incidents USA: New York, United States Committee on Large Dams, American Society of Civil Engineers, p. 127–128.

Connell, D.H., Solomon, E., and Rodda, K.V., 1985, Grouting solves complex seepage problems at Bell Canyon Dam, *in* Transactions: 15th International Congress on Large Dams, International Commission on Large Dams, Lausanne, June 24–28, v. 3, p. 591–611.

Corda, I.I., 1988, Iron Gates II—design and performance of dams—geotechnical considerations, *in* Proceedings: 2nd International Conference on Case Histories in Geotechnical Engineering, St. Louis, June 1–5, v. 1, p. 663–670.

Cornforth, D.H., and Mikkelsen, P.E., 2000, Continuous monitoring of groundwater response to winter rainfall, *in* Bromhead, E., Dixon, N., and Ibsen, M-L., eds., Landslides in research, theory and practice: Thomas Telford, London, Proceedings, 8th International Symposium on Landslides, Cardiff, Wales, June 26–30, v. 1, p. 323–328.

Cotton, W.R., 1972, Preliminary geologic map of the Franciscan rocks in the central part of the Diablo Range, Santa Clara and Alameda Counties, California: U.S. Geological Survey Basic Data Contribution 39, scale 1:62,500.

Coyne, A., 1939, Cours de barrages à l'Ecole Nationale Supérieure des Ponts et Chaussees: Paris.

Crandell, D.R., 1951, Preliminary report on the geology of the Pierre quadrangle, South Dakota: U.S. Geological Survey Open-File Report, 28 p.

Crandell, D.R., 1952, Landslides and rapid-flowage phenomena near Pierre, South Dakota: Economic Geology, v. 47, p. 548–568.

Crandell, D.R., 1958, Geology of the Pierre area, South Dakota: U.S. Geological Survey Professional Paper 307, 83 p.

Crosby, I.B., 1939, Engineering geology problems at Conchas Dam, New Mexico: American Society of Civil Engineers Proceedings, v. 65, January, p. 29–47.

Cruden, D.M., and Varnes, D.J., 1996, Landslide types and processes, *in* Turner, A.K., and Schuster, R.L., eds., Landslides—investigation and mitigation: Washington, D.C., National Academy Press, Transportation Research Board Special Report 247, p. 36–75.

Czechoslovak National Dam Committee, 1967, Dams in Czechoslovakia: Bratislava, 32 p.

da Costa Nunes, A.J., de M. Fernandez, C.E., Lima, A., 1982, Stabilization of dam abutments—Brazilian case histories, *in* Transactions: 14th International Congress on Large Dams, International Commission on Large Dams, Rio de Janeiro, May 3–7, v. 2, p. 859–876.

de la Torre, M., Garga, V., Novosad, S., Tordoya, J., and Mayta, J., 1997, Revaluación de la estabilidad del Derrumbe no. 5—Presa Tablachaca de la Central Hidroelectrica Mantaro, Peru, *in* Proceedings: 2nd Pan-American Symposium on Landslides, Rio de Janeiro, November, v. 2, p. 747–753.

de Luccia, E.R., 1958, Lewis River development, *in* Souvenir—U.S. dam study tours: Omaha District, Corps of Engineers, 6th International Congress on Large Dams, New York, September 15–20, p. 156–160.

Demirev, A., 1979, Engineering geological conditions of high dams in the folded regions of Bulgaria: International Association of Engineering Geology Bulletin, no. 20, p. 80–83.

Desio, A., 1973, Geologia applicata alla ingegneria: Hoepli, Milan, 1,194 p.

Dibblee, T.W., 1988, Geologic map of the Ventura and Pitas Point quadrangles: Santa Barbara, Calif., Dibblee Geological Foundation, scale 1:24,000.

Dibblee, T.W., 1980, Preliminary geologic map of the Las Trampas Ridge quadrangle, Alameda and Contra Costa Counties, California: U.S. Geological Survey Open-File Report 80-545, scale 1:24,000.

Dluzewski, J., Hrabowski, W., Opyrchal, L, and Tomaszewicz, A., 2000, Interactive control system of the abutment stability—Wisla-Czarne Dam site, *in* Transactions: 20th International Congress on Large Dams, International Commission on Large Dams, Beijing, September 19–22, v. 3, p. 51–58.

DNOCS, 1982, Dams in the northeast of Brazil—DNOCS experience in dams in semi-arid region: Fortaleza, Brazil, Ministry of Interior, National Department of Works Against Droughts, 158 p.

Dounias, G.T., Pantelidis, P.I., Marinos, P.G., and Vaughan, P.R., 1996, Landslide reactivation in flysch colluvia at the Evinos Dam site, *in* Senneset, K., ed., Landslides: Proceedings, 7th International Symposium on Landslides, Trondheim, June 17–21, v. 2, p. 1,201–1,206.

Dow, G., 1995, Engineering geology of Jordanelle Dam and Reservoir, Bonneville unit, central Utah project, Utah, *in* Lund, W.R., ed., Environmental & engineering geology of the Wasatch Front region: Proceedings, 1995 Utah Geological Association Symposium and Field Conference, Salt Lake City, September 22–23, Utah Geological Association Publication 24, p. 319–344.

Dunn, A.B., 1999, Geologic setting and preliminary hydrologic analysis of the Costilla Dam, New Mexico, landslide [abs.]: Geological Society of America Abstracts with Programs, v. 31, no. 7, p. A-286.

Dunn, A.B., 2000, Geology and hydrology of the Costilla Dam landslide, Taos County, New Mexico: Socorro, New Mexico Institute of Mining and Technology, M.S. thesis, number of pages not available.

Dunn, A.B., and Haneberg, W.C., 1998, Geologic setting of the Costilla Dam, New Mexico, landslide [abs.]: Association of Engineering Geologists Program with Abstracts, 41st Annual Meeting, Seattle, September–October, Errata to Technical Sessions, p. 4.

Eckerlin, R.D., 1992, Mud Mountain Dam concrete cutoff wall—a case history: Association of Engineering Geologists Bulletin, v. 29, no. 1, p. 11–32.

Eckerlin, R.D., 1993, Mud Mountain Dam concrete cutoff wall, *in* Anderson, L.R., ed., Geotechnical practice in dam rehabilitation: Proceedings of a specialty conference, American Society of Civil Engineers, Raleigh, N.C., April 25–28, p. 284–298.

Eisbacher, G.H., 1983, Slope stability, Southern Coast Mountains and Fraser Lowland: Field Trip Notes, Cordilleran Section, Geological Association of Canada, Vancouver, B.C., October 16, 46 p.

Ellis, M.S., and Gabaldo, V., 1989, Geologic map and cross sections of parts of the Grand Junction and Delta 30′×60′ quadrangles, west-central Colorado: U.S. Geological Survey Coal Investigations Map C-124, scale 1:100,000.

Engineering Division, 1958, Oahe Dam on the Missouri River, *in* Souvenir—U.S. dam study tours: Omaha District, Corps of Engineers, 6th International Congress on Large Dams, International Commission on Large Dams, New York, September 15–20, p. 65–72.

Engineering News-Record, 1937, Small earthfill dam fails: June 24, p. 932.

Evans, S.G., and Savigny, K.W., 1994, Landslides in the Vancouver-Fraser Valley-Whistler Region, *in* Monger, J.W.H., ed., Geology and geological hazards of the Vancouver Region, southwestern British Columbia: Geological Survey of Canada Bulletin 481, p. 251–286.

Everitt, B., 1993, Memorandum on phase II geologic review of Recapture Dam: Utah Division of Water Resources Memorandum, Salt Lake City, February 18, 9 p.

Everitt, B., and Schuster, R.L., 1999, Dams on landslides in Utah [abs.]: Association of Engineering Geologists Program with Abstracts, 42nd Annual Meeting, Salt Lake City, September 26–29, p. 64.

Federal Emergency Management Agency (U.S.), 1996, Water control infrastructure—National inventory of dams: Washington, D.C. (CD-ROM).

Fell, R., Hungr, O., Leroueil, S., and Riemer, W., 2000, Keynote lecture—geotechnical engineering of the stability of natural slopes, and cuts and fills, *in* GeoEng2000: Lancaster, U.K., Technomic Publishing Co., Inc., Proceedings, International Conference on Geotechnical & Geological Engineering, Melbourne, November 19–24, p. 21–120.

Fell, R., MacGregor, P., and Stapledon, D., 1992, Geotechnical engineering of embankment dams: Rotterdam, Balkema, 675 p.

Fernández, T., Irigaray, C., and Chacon, J., 1996, Inventario de movimientos de ladera en el borde noreste de la Sierra de Los Guájares (Granada) mediante un S.I.G., *in* Proceedings: 6th Spanish Congress and International Conference on Environmental Geology and Land-Use Planning, Granada, April 22–25, v. 1, p. 419–441.

Fernandez del Castillo, T., Brabb, E., Delgado Salazar, F., Martin-Algarra, A., Irigaray Fernandez, C., Estevez Rubio, A., and Chacon Montero, J., 1997, Rasgos geologicos y movimientos de ladera en el sector Izbor-Velez Benaudalla de la cuenca del Rio Guadalfeo (Granada), *in* Proceedings: 4th Simp. Nacional sobre Taludes y Laderas Inestables, Granada, November 11–14, p. 795–808.

Figueroa, M.C., Lhez, M.H., and Pronsato, M.A.D., 1976, Stability and drainage revision of dam and right bank “Quebrada de Ullum Project,” *in* Transactions: 12th International Congress on Large Dams, International Commission on Large Dams, Mexico City, March–April, v. 2, p. 17–26.

Fookes, P.G., Baynes, F.J., and Hutchinson, J.N., 2000, Total geological history—a model approach to the anticipation, observation and understanding of site conditions, *in* GeoEng2000: Proceedings, International Conference on Geotechnical & Geological Engineering, Melbourne, 19–24 November, v. 1, p. 370–460.

Fookes, P.G., and Dale, S.G., 1992, Comparison of interpretations of a major landslide at an earthfill dam site in Papua New Guinea: Quarterly Journal of Engineering Geology, v. 25, p. 313–330.

Fookes, P.G., Dale, S.G., and Land, J.M., 1991, Some observations on a comparative aerial photograph interpretation of a landslipped area: Quarterly Journal of Engineering Geology, v. 24, p. 249–265.

Forrest, M., Roadifer, J., and Leeflang, W., 2001, Long Park Dam rehabilitation—design and construction of seepage control system, *in* The future of dams and their reservoirs: 21st Annual USSD Lecture Series, United States Society on Dams, Denver, July 30–August 3, p. 59–73.

Foster, P.F., Amos, P.D., and Silvester, P.K., 2000, Monitoring of Clyde and Roxburgh gravity dams and their schist foundations, *in* Transactions: 20th International Congress on Large Dams, International Commission on Large Dams, Beijing, September 19–22, v. 3, p. 79–92.

Foster, P.F., Riddolls, B.W., and Macfarlane, D.F., 1996, Response of Clyde slide, New Zealand, to toe inundation, *in* Senneset, K., ed., Landslides: Proceedings, 7th International Symposium on Landslides, Trondheim, June 17–21, v. 2, p. 727–731.

Fukuoka, M., and Taniguchi, T., 1961, Research on landslides—Un exemple de grand glissement dans une masse de roche et de sol, *in* Proceedings: 5th International Conference on Soil Mechanics and Foundation Engineering, Paris, July 17–22, v. 2, p. 603–605.

Gagliardi, J., and Routh, R., 1993, Geotechnical modifications at Meeks Cabin Dam, *in* Anderson, L.R., ed., Geotechnical practice in dam rehabilitation: Proceedings of a specialty conference, American Society of Civil Engineers, Raleigh, N.C., April, p. 755–769.

Galster, R.W., 1989a, Howard A. Hanson Dam, *in* Galster, R.W., ed., Engineering geology in Washington: Washington Division of Geology and Earth Resources Bulletin 78, v. 1, p. 233–240.

Galster, R.W., 1989b, Mud Mountain Dam, *in* Galster, R.W., ed., Engineering geology in Washington: Washington Division of Geology and Earth Resources Bulletin 78, v. 1, p. 241–248.

García Yagüe, A., and Fernández Montero, A., 1986, Slope instabilities and site selections for the ‘Pas’ reservoir, Santander, Spain, *in* Proceedings: 5th International Congress, International Association of Engineering Geology, Buenos Aires, October 20–25, v. 2, p. 1,259–1,265.

Garga, V.K., and de la Torre, M., 2004, The Tablachaca slide no. 5, Peru—a 20-year post-remediation assessment, *in* Lacerda, W.A., Ehrlich, M., Fontoura, S.A.B., and Sayão, A.S.F., eds., Landslides—evaluation and stabilization: Leiden, the Netherlands, A.A. Balkema Publishers, Proceedings, 9th International Symposium on Landslides, Rio de Janeiro, June 28–July 2, v. 2, p. 1,691–1,696.

Gignoux, M., and Barbier, R., 1955, Geologie des barrages et des amenagements hydrauliques: Paris, Masson and Co., 343 p.

Gillon, M.D., and Hancox, G.T., 1991, Cromwell Gorge landslides—a general overview, *in* Bell, D.H., ed., Landslides: Proceedings, 6th International Symposium on Landslides, Christchurch, February 10–14, 1992, v. 1, p. 83–102.

Glover, T., Craddock, T., and Harder, L.F., Jr., 1997, Castaic Dam left abutment stability evaluation, *in* Proceedings: ASDSO Western Regional Conference, Association of State Dam Safety Officials, Oklahoma City, Okla., May 5–7, p. 105–126.

Goodman, R.E., 1993, Engineering geology—rock in engineering construction: New York, Wiley, 413 p.

Gordon, G., 1937, Arch dam of ice stops slide: Engineering News-Record, February 11, p. 211–215.

Graybeal, K.D., 1991, Seepage cutoff wall design and construction in Mud Mountain Dam, *in* Proceedings: 1991 Annual Conference, Association of State Dam Safety Officials, San Diego, September 29–October 2, v. 1, p. 91–107.

Grosman, M., and Lejsek, J., 1965, The Nechranice Dam under construction: Prague, Documentation Centre of the Management of Water Development, 40 p.

Gulick, C.W., and Korosec, M.A., 1990, Geologic map of the Banks Lake 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open-File Report 90-6, scale 1:100,000.

Haddaoui, M., and Benabbou, L., 1991, Travaux de confortement du barrage Nakhla, *in* Transactions: 17th International Congress on Large Dams, International Commission on Large Dams, Vienna, June 17–21, v. 1, p. 1,259–1,279.

Haffen, M., 1955, Barrage de la Chaudanne travaux de consolidation et d’étanchement, *in* Transactions: 5th International Congress on Large Dams, International Commission on Large Dams, Paris, May–June, v. 4, p. 1,105–1,119.

Hail, W.B., Jr., 1968, Geology of southwestern North Park and vicinity, Colorado: U.S. Geological Survey Bulletin 1257, 119 p., 3 pls.

Hall, C.A., Jr., 1978, Geologic map of Twitchell Dam and parts of Santa Maria and Tepusquet Canyon quadrangles, Santa Barbara County, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-933, scale 1:24,000.

Hamilton, P., 1992, Hydroelectric dams in the Sierras of the Southern California Edison Company, *in* Pipkin, B.W., and Proctor, R.J., eds., Engineering geology practice in Southern California: Belmont, Calif., Star Publishing Company, Association of Engineering Geologists, Southern California Section, Special Publication 4, p. 667–678.

Hammer, G., 2002, If it ain’t broke….or is it?, *in* Dam safety: Proceedings, 2002 Annual Conference, Association of State Dam Safety Officials, Tampa, Florida, September 8–11, p. 43–49.

Hammond, C.M., 1999, Frog Lake landslide and dam reconstruction, northern Oregon Cascades [abs.]: Association of Engineering Geologists Program with Abstracts, 42nd Annual Meeting, Salt Lake City, Utah, September 26–29, p. 67.

Hammond, C.M, and Griffiths, J.B., 1998, An overview of engineering geology applied to facilities in Oregon, *in* Burns, S., ed., Environmental, groundwater and engineering geology—applications from Oregon: Belmont, Calif., Star Publishing Company, p. 27–33.

Haneberg, W.C., 1999, Reactivation of the Costilla Dam, New Mexico, landslide during dam reconstruction [abs.]: Geological Society of America Abstracts with Programs, 1999 Annual Meeting, Denver, October 25–28, v. 31, no 7, p. A-286.

Hanegan, G.L., 1973, Castaic Dam—a case history of geologic engineering problems and their solutions, *in* Moran, D.E., Slosson, J.E., Stone, R.O., and Yelverton, C.A., eds., Geology, seismicity, and environmental impact: Association of Engineering Geologists Special Publication, p. 201–211.

Harty, K, 1991, Landslide map of Utah: Utah Geological and Mineral Survey, 28 p. plus map (scale 1:500,000).

Haws, E.T., Martin, P.L., and Yu, T.H., 1985, Devil's Dingle ash disposal works dam, *in* Proceedings: 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, August 12–16, v. 3, p. 1,253–1,256.

Hayes, G.S., 1981, Geologic stability of Mystic Lake Dam, Gallatin County, Montana, and computer simulation of potential flood hazards from failure of the dam: Bozeman, Montana State University, M.S. thesis, 120 p.

Heidstra, N.N., Murray, L.M., Morrison, M.A., and Archibald, P.R., 1995, Seismic upgrading of Seymour Falls Dam, *in* Waterpower '95: American Society of Civil Engineers, an International Conference & Exposition on Hydropower, San Francisco, July, not paginated.

High Country Independent Press, 1985, Mystic Dam breached: Bozeman, Mont., March 27, p. 5.

Hobst, L., and Zajíc, J., 1983, Anchoring in rock and soil: Amsterdam, Elsevier, 570 p.

Holdredge, C.P., 1957, Geologic reports on damsites in the John Day Basin, Oregon, *in* Trask, P.D., ed., Engineering geology case histories: Geological Society of America, no. 1, p. 25–32.

Holton, D., 1983, Flood—highway reopened after dam collapse: Daily Argus Observer, Ontario, Oreg., April 1, p. 1.

Horský, O., and Spanilá, T., 1997, Remodeling of water reservoir banks by exogenous processes, *in* Marinos, P.G., Koukis, G.C., Tsiambaos, G.C., and Stournaras, G.C., eds., Engineering geology and the environment: Proceedings, International Symposium on Engineering Geology and the Environment, International Association of Engineering Geology, Athens, June 23–27, v. 3, p. 2,711–2,716.

Horswill, P., and Horton, A., 1976, Cambering and valley bulging in the Gwash valley at Empingham, Rutland: Royal Society of London Philosophical Transactions, A, v. 283, p. 427–462.

Howell, P.W., 1952, Geologic background of slides at Lookout Point Reservoir, Oregon: Proceedings of the Oregon Academy of Science, v. 3, p. 32.

Hrdy, J., and Mares, I., 1978, Rock slide in the right bank of the Dalešice Dam, *in* Proceedings: 3rd International Congress, International Association of Engineering Geology, Madrid, September, Section 3, v. 1, p. 152–155.

Hunter, J.B., 1982, Some examples of design changes required during construction, *in* Balasubramaniam, A.S., Yudhbir, and Tomiolo, A., eds., Proceedings: International Symposium on Geotechnical Problems and Practice of Engineering, Bangkok, December, p. 99–108.

Hunter, J.F., 1918, Mosca Reservoir, *in* Atwood, W.W., Relation of landslide and glacial deposits to reservoir sites in the San Juan Mountains, Colorado: U.S. Geological Survey Bulletin 685, p. 26–29.

Hutchinson, J.N., 1988, General report—Morphological and geotechnical parameters of landslides in relation to geology and hydrology, *in* Bonnard, C., ed., Landslides: Rotterdam, A.A. Balkema, Proceedings, 5th International Symposium on Landslides, v. 1, p. 3–35.

International Commission on Large Dams, 1974, Lessons from dam incidents: Paris, 1,069 p.

International Commission on Large Dams, 1983, Deterioration of dams and reservoirs: Paris, December, 367 p.

Irwin, W.H., 1938, Geology of the rock foundation of Grand Coulee Dam, Washington: Geological Society of America Bulletin, v. 49, p. 1,627–1,650.

Ischy, E., and Haffen, M., 1955, Barrage de Serre-Ponçon, campagnes de reconnaissances, *in* Transactions: 5th International Congress on Large Dams, International Commission on Large Dams, Paris, May–June, v. 1, p. 803–831.

Izett, G.A., and Barclay, C.S.V., 1973, Geologic map of the Kremmling quadrangle, Grand County, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1115, scale 1:62,500.

Jalote, S.P., Shome, S.K., and Mehta, P.N., 1975, Yamuna Hydel Scheme, Uttar Pradesh, *in* Engineering geology case histories: Geological Survey of India Miscellaneous Publication 29, part 1, p. 118–130, part 2, pl. 37.

Jalote, S.P., and Tikku, A.K., 1975, Beas Dam project, *in* Engineering geology case histories: Geological Survey of India Miscellaneous Publication 29, part 1, p. 107–117, part 2, pl. 34.

Japanese National Committee on Large Dams, 1979, Dams in Japan: no. 8, 63 p.

Jaspar, J.L., and Peters, N., 1979, Foundation performance of Gardiner Dam: Canadian Geotechnical Journal, v. 16, p. 758–788.

Jensen, J.R., 1981, Swift hydro-electric project, *in* Engineering geology in the Pacific Northwest: Association of Engineering Geologists Field Trip Guidebook, 24th Annual Meeting, Portland, Oreg., September–October, p. 186–193.

Kawashima, T., and Kanazawa, K., 1982, Design of rockfill dams on weathered foundation with large scale faults, *in* Transactions: 14th International Congress on Large Dams, International Commission on Large Dams, Rio de Janeiro, May 3–7, v. 2, p. 75–99.

Keech, C.E., and Sanford, B.A., 1998, Tooth Rock landslide, Columbia Gorge, Oregon, *in* Burns, S., ed., Environmental, groundwater and engineering geology—applications from Oregon: Belmont, Calif., Star Publishing Company, p. 367–372.

Kehew, A.E., 1983, Geology and geotechnical conditions of the Minot area, North Dakota: North Dakota Geological Survey Report of Investigations 73, 35 p.

Kent, M.D., 1981, Geology of the Warm Springs-Pelton area, *in* Field trip guidebook: Association of Engineering Geologists, 24th Annual Meeting, Portland, Oreg., September 27–October 2, p. 57–69.

Kiersch, G.A., and James, L.B., 1991, Errors of geologic judgment and the impact on engineering works, *in* Kiersch, G.A., ed., The heritage of engineering geology; the first hundred years: Geological Society of America, Centennial Special Vol. 3, p. 517–558.

Kintzer, F.C., 1980, Geology and landslides at Calaveras Reservoir, Alameda and Santa Clara Counties, California: Hayward, California State University, M.S. thesis, 138 p.

Kirkaldie, L., and Thomas, L.E., 1984, Dissecting a dam: Association of Engineering Geologists Bulletin, v. 21, no. 4, p. 509–514.

Knight, D.K., 1963, Oahe Dam—geology, embankment, and cut slopes: Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers, v. 89, no. SM2, p. 99–125.

Kocahan, H.T., and Taylor, G.M., 2002, Rehabilitation of Black Rock Dam—“seepage and inadequate spillway,” *in* Dam safety: Proceedings, 2002 Annual Conference, Association of State Dam Safety Officials, Tampa, Fla., September 8–11, p. 223–240.

Konteatis, C.A.C., 1974, Dams of Cyprus: Nicosia, Republic of Cyprus, Ministry of Agriculture and Natural Resources, 264 p.

Krapp, L., and Pantzartzís, P., 1989, Besondere ingenieurgeologische und hydrogeologische Aufgaben beim Talsperrenbau in N. Griechenland: Mitt. Ing.-u. Hydrogeologie, RWTH Aachen, v. 32, p. 77–107.

Kropatschek, H., and Rienössl, K., 1967, Travaux d’étanchement du sous-sol du barrage de Durlassboden, *in* Transactions: 9th International Congress on Large Dams, International Commission on Large Dams, Istanbul, September 4–8, v. 1, p. 695–713.

Kumara, H.M.A., and Kulasinghe, A.N.S., 1986, Studies of slope stability problems in the Kotmale Hydropower Project area—Sri Lanka, *in* Gardiner, V., ed., International geomorphology 1986: Chichester, U.K., Wiley, Proceedings, 1st International Conference on Geomorphology, Part I, p. 111–119.

Kunzer, A., 1998, Spillway modifications—Ochoco Dam, Crooked River project, Oregon, *in* Proceedings: 33rd Symposium on Engineering Geology and Soils Engineering, Reno, Nev., March 25–27, p. 37–47.

Lapworth, H., 1911, The geology of dam trenches: Institution of Water Engineers Transactions, London, v. 16, p. 25–66.

Lauffer, H., and Schober, W., 1964, The Gepatsch rockfill dam in the Kauner, *in* Transactions: 8th International Congress on Large Dams, International Commission on Large Dams, Edinburgh, May 4–8, v. 3, p. 635–660.

Lavania, B.V.K., 1988, Treatment of left bank slopes of Ichari Dam, *in* Proceedings: 2nd International Conference on Case Histories in Geotechnical Engineering, St. Louis, p. 621—625.

Legget, R.F., 1939, Geology and engineering: New York, McGraw-Hill, 650 p.

Legget, R.F., and Hatheway, A.W., 1988, Geology and engineering: New York, McGraw-Hill, 613 p.

Legget, R.F., and Karrow, P.F., 1983, Handbook of geology in civil engineering: New York, McGraw-Hill, 50 chap [variously paged].

Lemke, R.W., 1960, Geology of the Souris River Area, North Dakota: U.S. Geological Survey Professional Paper 325, 138 p.

Leobacher, A., 2000, Detection of abnormal leakage at Eberlaste earthfill dam, *in* Transactions: 20th International Congress on Large Dams, International Commission on Large Dams, Beijing, September 19–22, v. 3, p. 1,221–1,233.

Li, J., and Luo, D., 1981, The formation and characteristics of mudflow and flood in the mountain area of the Dachao River and its prevention: Zeitung Geomorphologie N.F., v. 25, no. 4, p. 470–484.

Lilly, R.N., 1986, Wungong Dam landslide: Australian National Committee on Large Dams Bulletin 74, p. 38–49.

Lipman, P.W., 1975, Geologic map of the Lower Conejos River Canyon, southeastern San Juan Mountains, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-901, scale 1:48,000.

Lockhart, A.C., 1998, Agate Dam, Jackson County, southern Oregon, *in* Burns, S., ed., Environmental, groundwater and engineering geology—applications from Oregon: Belmont, Calif., Star Publishing Company, p. 127–131.

Logan, M.H., and Davis, F.J., 1972, Landslide at Silver Jack Dam, *in* Proceedings: Specialty Conference on Performance of Earth and Earth-supported Structures, American Society of Civil Engineers, Purdue University, West Lafayette, Ind., June, v. 3, p. 315–325.

Lopez Marinas, J.M., Gaztañaga, J.M., and Cajete, J., 1997, Landslides in the Cortes Reservoir (River Júcar, Valencia, Spain) during initial filling, *in* Transactions: 19th International Congress on Large Dams, International Commission on Large Dams, Florence, May 26–30, v. 3, p. 537–550.

Lordet, J., Duquennois, H., and Guilhamon, J., 1955, Hydroelectric development of the Oued Agrioun, *in* Review travaux: 5th International Congress on Large Dams, International Commission on Large Dams, Paris, May–June, Supplement no. 247, p. 190–206.

Lowe, J., III, 1988, Earthfill dams, *in* Kollgard, E.B., and Chadwick, W.L., eds., Development of dam engineering in the United States: New York, Pergamon Press, Prepared in commemoration of the 16th International Congress on Large Dams, United States Committee on Large Dams, p. 671–884.

Lukáč, M., 1985, Measures for limiting seepages in the foundation of two earth dams in operation, *in* Transactions: 15th International Congress on Large Dams, International Commission on Large Dams, Lausanne, June 24–28, v. 3, p. 643–651.

Macfarlane, D.F., and Gillon, M.D., 1995, The performance of landslide stabilization measures, Clyde power project, New Zealand, *in* Bell, D.H., ed., Landslides: Proceedings, 6th International Symposium on Landslides, Christchurch, February 10–14, 1992, v. 3, p. 1,747–1,757.

Machette, M.N, Anderson, R.E., Joyner, W.R., Schuster, R.L., and Swolfs, H.S., 1991, Review of geotechnical aspects of the Jordanelle damsite, Heber, Utah: U.S. Geological Survey Open-File Report 91-398, 43 p.

Madole, R.F., 1982, Surficial geologic map of the Craig ½º×1º quadrangle, Moffat and Routt Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1346, scale 1:100,000.

Madole, R.F., 1989, Surficial geologic map of the Meeker 30′×60′ quadrangle, Garfield, Moffat, Rio Blanco, and Routt Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1823, scale 1:100,000.

Madole, R.F., 1991a, Surficial geologic map of the Steamboat Springs 30′×60′ quadrangle, Grand, Jackson, and Routt Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1825, scale 1:100,000.

Madole, R.F., 1991b, Surficial geologic map of the Walden 30′×60′ quadrangle, Jackson, Larimer, and Routt Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1824, scale 1:100,000.

Major, J.J., and Scott, K.M., 1988, Volcaniclastic sedimentation in the Lewis River valley, Mount St. Helens, Washington—processes, extent, and hazards: U.S. Geological Survey Bulletin 1383-D, 38 p.

Malgot, J., Baliak, F., and Kopecký, M., 2002, Assessment of the Liptovská Mara landslide, *in* Rybář, J., Holzer, R., and Kopecký, M., eds., Post-conference field trip guide, east of the Czech Republic and Slovakia: 1st European Conference on Landslides, Prague, June, p. 48–51.

Marsal, R.J., and Reséndiz, D., 1971, Effectiveness of cutoffs in earth foundations and abutments of dams, *in* Proceedings: 4th Panamerican Conference on Soil Mechanics and Foundation Engineering, San Juan, Puerto Rico, June, v. 1, p. 237–312.

Martin, D.O., 1974, Understanding and treatment of dam foundations, *in* Lessons from dam incidents: International Commission on Large Dams, Paris, p. 245–263.

McLaughlin, R.J., Clark, J.C., Brabb, E.E., and Helley, E.J., 1991, Geologic map and structure sections of the Los Gatos 7.5′ quadrangle, Santa Clara and Santa Cruz Counties, California: U.S. Geological Survey Open-File Report 91-593, 50 p. plus 3 maps, scale 1:24,000.

Mencl, V., 1977, Modern methods used in the study of mass movements: International Association of Engineering Geology Bulletin, no. 16, p. 185–197.

Mignon, K., 1968, Zur Geologie im Raume der Oberstufe des Gerloskraftwerkes: Österreichische Zeitschrift für Elektrizitätwirtschaft, v. 21, no. 8, p. 391–397.

Mikuni, E., 1980, Dam engineering activities in Japan, *in* Balasubramaniam, A.S., Yudhbir, and Tomiolo, A., eds., Proceedings: Symposium on Geotechnical Problems and Practice of Dam Engineering, Bangkok, December 1–15, p. 109–130.

Millet, R.A., Lawton, G.M., Repetto, P.C., and Garga, V.K., 1992, Stabilization of Tablachaca Dam landslide, *in* Proceedings: Specialty Conference on Stability and Performance of Slopes and Embankments, Berkeley, Calif., June 29–July 1, v. 2, p. 1,365–1,381.

Mohammadi, A., Kessler, D., Doane, J., and Vessely, A., 2000, An integrated strategy for seepage control from Bull Run #2 spillway approach canal, *in* Proceedings: 20th International Congress on Large Dams, International Commission on Large Dams, Beijing, September 19–22, v. 3, p. 687–702.

Montgomery S.B., 1980, Geologic map of Recapture Creek Dam & Reservoir Site: Utah Division of Water Resources, Salt Lake City, scale 1:1200.

Moore, D.P., and Mathews, W.H., 1978, The Rubble Creek landslide, southwestern British Columbia: Canadian Journal of Earth Sciences, v. 15, no. 7, p. 1,039–1,052.

Morales Arnao, B., Garga, V.K., Wright, R.S., and Perez, J-Y., 1984, The Tablachaca slide no. 5, Peru, and its stabilization, *in* Proceedings, 4th International Symposium on Landslides, Toronto, September 16–21, v. 1, p. 597–604.

Moreno, H., Thiele, R., and Varela, J., 1991, Estudio Geologico y de Riesgo Volcanico y de Remocion en Masa del Proyecto Hidroelectrico Alfalfal II–Las Laja: Report for CHILGENER, Santiago, Chile, number of pages not available.

Morton, D.M., and Streitz, R., 1969, Preliminary reconnaissance map of major landslides, San Gabriel Mountains, California: California Division of Mines and Geology Map Sheet 15, scale 1:63,360.

Mumford, J.A., 1994, Public response to emergency evacuation of Ochoco Reservoir, *in* Proceedings: 1994 Annual Conference, Association of State Dam Safety Officials, Boston, September 11–14, p. 513–517.

Neff, G.E., 1989, Columbia Basin Project, *in* Galster, R.W., ed., Engineering geology in Washington: Washington Division of Geology and Earth Resources Bulletin 78, v. 1, p. 539–563.

Nemcok, A., 1982, Zosuvy v Slovenských Karpatoch: VEDA, vydavaatel'stvo Slovenskej akadémie vied, Bratislava, 319 p.

Newman, F.B., Curtiss, R.E., Jr., Gower, T.R., and Roth, B.L., 2000, Stabilization of landslide at McElroy's Run impoundment using auger cast grout columns, *in* Tailings dams 2000: Proceedings, Tailings Dam 2000 Conference, Association of State Dam Safety Officials, Las Vegas, Nev., March 28–30, p. 187–196.

New Zealand Geomechanics Society, 1992, Guide to landslides technical tour: Sixth ISL Pre-Symposium Field Seminar, 6th International Symposium on Landslides, Queenstown, New Zealand, February 8, 15 p., plus attachments.

Nilsen, T.H., 1972a, Preliminary photointerpretation map of landslide and other surficial deposits of parts of the Los Gatos, Morgan Hill, Gilroy Hot Springs, Pacheco Pass, Quien Sabe, and Hollister 15-minute quadrangles, Santa Clara County, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-416, scale 1:62,500.

Nilsen, T.H., 1972b, Preliminary photointerpretation map of landslide and other surficial deposits of the Mount Hamilton quadrangle and parts of the Mount Boardman and San Jose quadrangles, Alameda and Santa Clara Counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-339, scale 1:62,500.

Nilsen, T.H., 1973, Preliminary photointerpretation map of landslide and other surficial deposits of the Concord 15-minute quadrangle and the Oakland West, Richmond, and part of the San Quentin 7 ½-minute quadrangles, Contra Costa and Alameda Counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-493, scale 1:62,500.

Norfleet, J., and Marvin, B., 1995, Monument Dam—a case study—instrumentation of landslide enables continued operation of reservoir without compromising safety, *in* Proceedings: 1995 Annual Conference, Association of State Dam Safety Officials, Atlanta, September 17–20, p. 705–714.

Novosad, S., 1979, Establishing conditions of equilibrium of landslides in dam reservoirs by means of geoacoustic (rock noise) method: International Association of Engineering Geology Bulletin 20, p. 138–144.

Novosad, S., 1990, Evaluation and mitigation of geologic hazard related to the construction of Slezska Harta Dam on the Moravice River in Czechoslovakia, *in* Proceedings: 6th International Congress, International Association of Engineering Geology, Amsterdam, August 6–10, v. 2, p. 1,941–1,948.

Novosad, S., Barvinek, R., and de la Torre Sabrevilla, M., 1979, Estudio de estabilidad del Derrumbe No. 5 en el Reservorio de Tablachaca de la Central Hidroelectrica del Mantaro, *in* Proceedings: 6th Panamerican Conference on Soil Mechanics and Foundation Engineering, Lima, December, v. 1, p. 331–344.

Novosad, S., and Novosad, L., eds., 1993, Field work shop guide—CS (Czechoslovak) landslide field trip: 7th ICFL (International Conference and Field Workshop on Landslides), Prague, August 28–September 15, number of pages not available.

Ohta, H., Tokida, K., Tsunaki, R., Ohmori, K., and Ozou, H., 1996, Case study of a colossal rock mass slide along discontinuity surface, *in* Senneset, K., ed., Landslides: Proceedings, 7th International Symposium on Landslides, Trondheim, June 17–21, v. 2, p. 841–846.

Okuno, T., Wang, F.W., and Matsumoto, T., 2004, The deforming characters of the giant Jinnosuke-dani landslide in Haku-san mountainous area, Japan, *in* Lacerda, W.A., Ehrlich, M., Fontoura, S.A.B., and Sayão, A.S.F., eds., Landslides—evaluation and stabilization: Leiden, the Netherlands, A.A. Balkema Publishers, Proceedings, 9th International Symposium on Landslides, Rio de Janeiro, June 28–July 2, v. 2, p. 1,279–1,285.

O'Reilly, R.P., 1958, Hydroelectric development on the Clackamas River, Oregon, *in* Souvenir—U.S. dam study tours: 6th International Congress on Large Dams, Omaha District, Corps of Engineers, New York, September 15–20, p. 150–155.

Oriel, S.S., and Moore, D.W., 1985, Geologic map of the West and East Palisades Roadless Areas, Idaho and Wyoming: U.S. Geological Survey Miscellaneous Field Studies Map MF-1619-B, scale 1:50,000.

Outland, C.F., 1977, Man-made disaster; the story of the St. Francis Dam: Glendale, Calif., Arthur H. Clark Company, 275 p.

Palmer, L., 1977, Large landslides of the Columbia River Gorge, Oregon and Washington, *in* Coates, D.R., ed., Reviews in engineering geology: Geological Society of America, v. 3, p. 69–83.

Pardini, R.J., and Reichert, G.A., 1993, Austrian Dam spillway replacement, *in* Proceedings: 1993 Annual Conference, Association of State Dam Safety Officials, Kansas City, Mo., September 26–29, p. 473–478.

Paterson, S.J., 1971, Engineering geology of the Lemonthyme hydro-electric scheme, Tasmania: Civil Engineering Transactions, Australian Institution of Engineers, April, p. 17–24.

Peters, N., and Long, W.C., 1981, Performance monitoring of dams in western Canada, *in* Kulhawy, F.H., ed., Proceedings: Geotechnical Engineering for Hydro Projects—Embankment Dam Instrumentation Performance, Engineering Geology Aspects, Rock Mechanics Studies, American Society of Civil Engineers, New York, May 11–12, p. 23–45.

Philbrick, S.S., 1976, Kinzua Dam and the glacial foreland, *in* Coates, D.R., ed., Geomorphology and engineering: Stroudsburg, Pa., Dowden, Hutchinson & Ross, Inc., p. 175–197.

Picarelli, L, and Russo, C., 2004, Remarks on the mechanics of slow active landslides and the interaction with man-made works, *in* Lacerda, W.A., Ehrlich, M., Fontoura, S.A.B., and Sayão, A.S.F., eds., Landslides—evaluation and stabilization: Leiden, the Netherlands, A.A. Balkema Publishers, Proceedings, 9th International Symposium on Landslides, Rio de Janeiro, June 28–July 2, v. 2, p. 1,141–1,176.

Popov, N., 1999, Debris flows and their control in Alma-Ata, Kazakhstan, *in* Sassa, K., ed., Landslides of the world: Kyoto, Kyoto University Press, p. 279–284.

Pronsato, M.A.D, Figueroa Castellanos, M.C., and Lhez, M.H.H., 1973, Spillway design criteria of the “Quebrada de Ullum” Reservoir—San Juan River, *in* Transactions: 11th International Congress on Large Dams, International Commission on Large Dams, Madrid, June 11–15, v. 2, p. 871–886.

Qi, X., 1986, Evolution of geological environment with water resources and hydropower constructions, *in* Proceedings: 5th International Congress, International Association of Engineering Geology, Buenos Aires, October 20–25, v. 4, p. 1,161–1,172.

Radbruch-Hall, D.H., and Varnes, D.J., 1976, Landslides—cause and effect: International Association of Engineering Geology Bulletin 14, p. 205–216.

Rambert, O., and Gavard, M., 1961, Foundation investigation and treatment, *in* Barrages en Suisse, course on water and energy: 7th International Congress on Large Dams, International Commission on Large Dams, Rome, June 26–July 1, p. 3–5.

Ramirez Reynaga, M., 1998, Landslide at right abutment of Los Naranjos Dam, Mexico, *in* Proceedings: 8th International Congress, International Association of Engineering Geology, Vancouver, September 21–25, v. 5, p. 3,087–3,094.

Rattue, D.A., Hammamji, Y., and Tournier, J-P., 2000, Performance of the Sainte Marguerite-3 Dam, during construction and reservoir filling, *in* Transactions: 20th International Congress on Large Dams, International Commission on Large Dams, Beijing, September 19–22, p. 899–915.

Rattue, D.A., Hammamji, Y., Virolle, F., and Tournier, J.P., 1999, Foundation treatment of the SM-3 dam, *in* Turfan, M., ed., Proceedings: International Symposium on Dam Foundations and Solutions, Antalya, Turkey, September 23, p. 755–766.

Reheis, M.C., 1984, Geologic map and coal sections of the Thornburgh quadrangle, Moffat and Rio Blanco Counties, Colorado: U.S. Geological Survey Coal Investigations Map C-100, scale 1:24,000.

Repetto, P.C., 1985, The Tablachaca Dam slide no. 5 problem, *in* Proceedings: 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, August 16–21, v. 5, p. 2,599–2,610.

Richey, J.E., 1959, Dam foundations in argillaceous strata: Water Power, February, p. 57–63.

Richey, J.E.,1964, Elements of engineering geology: London, Sir Isaac Pitman & Sons Ltd., 157 p.

Riemer, W., 1995, Keynote paper—landslides and reservoirs, *in* Bell, D.H., ed., Landslides: Proceedings, 6th International Symposium on Landslides, Christchurch, February 10–14, 1992, v. 3, p. 1,973–2,004.

Riemer, W., Pantzartzís, P., Krapp, L., and Scourtis, C., 1996, Investigation and monitoring of landslides at the Polyphyton project, *in* Senneset, K., ed., Landslides: Proceedings, 7th International Symposium on Landslides, Trondheim, June 17–21, v. 1, p. 357–362.

Rienössl, K., and Schnelle, P., 1976, The Durlassboden and Eberlaste embankments large settlements and underseepage in the overburden, *in* Transactions: 12th International Congress on Large Dams, International Commission on Large Dams, Mexico City, March 29–April 2, v. 2, p. 231–245.

Ringheim, A.S., 1964, Experiences with the Bearpaw Shale at the South Saskatchewan River Dam, *in* Transactions: 8th International Congress on Large Dams, International Commission on Large Dams, Edinburgh, May 4–8, v. 1, p. 529–550.

Ripley, C.F., and Campbell, D.B., 1963, Earthdam on compressible and pervious foundation: Division Paper of the Engineering Institute of Canada, EIC-63-Geotech 1, v. 1, no. 19, 18 p.

Roberts, A.E., 1964, Geologic map of the Mystic Lake quadrangle, Montana: U.S. Geological Survey Miscellaneous Geological Investigations Map I-398, scale 1:24,000.

Rogers, J.D., 1992, Reassessment of the St. Francis Dam failure, *in* Pipkin, B.W., and Proctor, R.J., eds., Engineering geology practice in Southern California: Belmont, Calif., Star Publishing Company, Association of Engineering Geologists Special Publication 4, p. 639–666.

Rogers, J.D., 1995, A man, a dam and a disaster—Mulholland and the St. Francis Dam, *in* Nunis, D.D., Jr., ed., The St. Francis Dam disaster: Los Angeles, Historical Society of Southern California, p. 1–109.

Rogers, J.D., 1997, Man-made disaster at an old landslide dam site, *in* Ehrenspect, H.E., and Powell, J.R., eds., A day in the field with Thomas Dibblee and J. David Rogers, St. Francis Dam area: Santa Barbara, Calif., Thomas Wilson Dibblee, Jr., Geological Foundation, p. 26–103.

Roy, S., 1975, Jaldhaka hydroelectric project–I stage, West Bengal, *in* Engineering geology case histories: Geological Survey of India Miscellaneous Publication 29, part 1, p. 199–206.

Saber, R.T., Barranco, A.P., Jr., Wilson, D.B., Finucane, R.B., and Snyder, M.R., 2001, Performance evaluation of Waterbury Dam, *in* The future of dams and reservoirs: 21st Annual USSD Lecture Series, United States Society on Dams, Denver, July 30–August 3, p. 75–98.

Sager, J.W., 1989, Bonneville Dam, *in* Galster, R.W., ed., Engineering geology in Washington: Washington Division of Geology and Earth Resources Bulletin 78, v. 1, p. 337–346.

Sager, J.W., and Budai, C.M., 1989, Geology and construction of the Spirit Lake outlet tunnel, Mount St. Helens, Washington, *in* Galster, R.W., ed., Engineering geology in Washington: Washington Division of Geology and Earth Resources Bulletin 78, v. 2, p. 1,229–1,234.

Sanders, J., Smith, K., and Thom, J.H., 2001, Nevada Creek Dam rehabilitation—save your old spillway for a very rainy day, *in* The future of dams and their reservoirs: 21st Annual USSD Lecture Series, United States Society on Dams, Denver, July 30–August 3, p. 151–164.

Sanganeria, J.S., 1975, Ranaptrap Sagar project, Chambal Valley development scheme, stage II, *in* Engineering geology case histories: Geological Survey of India Miscellaneous Publication 29, part 1, p. 41–49, part 2, pl. 15.

Schetelig, K., 1989, Eine ausgedehnte Felssackungszone am Mornos-Damm in Griechenland: Mitt. Ing. u. Hydrogeologie, Aachen, v. 5, no. 3, p. 13–39.

Schnitter, G., 1961, Earth dams, *in* Barrages en Suisse, Course on water and energy: 7th International Congress on Large Dams, International Commission on Large Dams, Rome, June 26–July 1, p. 31–32.

Schober, W., 1970, The interior stress distribution of the Gepatsch rockfill dam, *in* Transactions: 10th International Congress on Large Dams, International Commission on Large Dams, Montreal, June 1–5, v. 1, p. 169–187.

Schroeder, W.L., Phelps, R.E., and Tigoulet, A., 1988, Underwater construction of an impervious dam core, *in* Proceedings: 24th Symposium on Engineering Geology & Soils Engineering, Coeur d'Alene, Idaho, February 29–March 2, p. 391–407.

Schulz, M.G., 1980, The quantification of soil mass movements and their relationship to bedrock geology in the Bull Run watershed, Multnomah and Clackamas Counties, Oregon: Corvallis, Oregon State University, M.S. thesis, 170 p.

Schuster, R.L., 1989, Engineering geologic effects of the 1980 eruptions of Mount St. Helens, *in* Galster, R.W., ed., Engineering geology in Washington: Washington Division of Geology and Earth Resources Bulletin 78, v. 2, p. 1,203–1,228.

Schuster, R.L., 2003, Dams built on pre-existing landslides—the Colorado experience, *in* Boyer, D., Rogers, W.P., and Santi, P.M., eds., Engineering geology of Colorado: Association of Engineering Geologists, Rocky Mountain Section, Denver, 32 p. (CD-ROM).

Schuster, R.L., and Pringle, P.T., 2002, Engineering history and impacts of the Bonneville landslide, Columbia River Gorge, Washington-Oregon, U.S.A., *in* Rybář, J., Stemberk, J., and Wagner, P., eds., Landslides: Proceedings, 1st European Conference on Landslides, Prague, June 24–26, p. 59–78.

Secretaría de Recursos Hidráulicos, 1976a, Behavior of dams built in Mexico: Contribution to 12th International Congress on Large Dams, International Commission on Large Dams, Mexico City, March–April, Comisión Federal de Electricidad, 587 p.

Secretaría de Recursos Hidráulicos, 1976b, Grandes presas de Mexico 1976: Mexico City, 244 p.

Sen, P., Subba Rao, C., and Krishnamurthy, G.S., 1987, Case history of foundation remedial measures for a high rockfill dam, *in* Proceedings: International Symposium on New Materials and Techniques in Dam Construction, Central Board of Irrigation and Power, Madras, India, March 5–7, p. 43–47.

Sezginer, Y., and Karacaoğlu, B., 1961, Effectiveness of the pile cutoff in Selevir Dam, *in* Transactions: 9th International Congress on Large Dams, International Commission on Large Dams, Istanbul, September 4–8, v. 1, p. 595–608.

Shannon, W.D., and Shannon, W.L., 1954, Connell Dam provides water supply for Alaska's first pulp mill: Civil Engineering, American Society of Civil Engineers, v. 24, no. 6, p. 359–363.

Sharma, R.P., Jackson, H.E., and Kumar, S., 1997, Effects of the January 17, 1994, Northridge earthquake on Pacoima arch dam and interim remedial repairs, *in* Transactions: 19th International Congress on Large Dams, International Commission on Large Dams, Florence, May 26–30, v. 4, p. 127–151.

Sheko, A.I., 1988, Protection and control measures, *in* Kozlovskii, E.A., ed., Landslides and mudflows: United Nations Educational, Scientific and Cultural Organization/United Nations Environment Programme, Moscow, v. 1, p. 225–235.

Sherard, J.L., Woodward, R.J., Gizienski, S.F., and Clevenger, W.A., 1963, Earth and earth-rock dams—engineering problems of design and construction: New York, Wiley, 725 p.

Simmler, H., ed., 1977, Large dams in Austria: Österreichische Staubeckencommission, Vienna, 275 p. [translator: R. Partl].

Simpson, D.T., and Schmoll, M., 2001, Exploration, design, and construction of Los Vaqueros Dam, Contra Costa County, California, *in* Ferriz, H., and Anderson, R., eds., Engineering geology practice in Northern California: California Geological Survey Bulletin 210, Association of Engineering Geologists Special Publication 12, p. 297–310.

Skempas, M., and Chandler, R.J., 1993, Case histories of dams with abutment problems, *in* Anagnostopoulos, A., Schlosser, F., Kalteziotis, N., and Frank, R., eds., Geotechnical engineering of hard soils–soft rocks: Proceedings of an international symposium, Athens, September 20–23, p. 1,319–1,325.

Snyder, D.T., and Brownell, D.L., 1996, Hydrogeologic setting and preliminary estimates of hydrologic components for Bull Run Lake and the Bull Run Lake drainage basin, Multnomah and Clackamas Counties, Oregon: U.S. Geological Survey Water Resources Investigations Report 96-4064, 47 p.

Solomon, B.J., 1999, Surficial geologic map of the West Cache fault zone and nearby faults, Box Elder and Cache Counties, Utah: Utah Geological Survey Map 172, scale 1:24,000.

Soule, J.M., 1986, Vega Reservoir access road and vicinity—assessment of landslide hazards and related problems: Colorado Geological Survey Open-File Report 86-6, map scale 1:4,800.

Soule, J.M., 1988, Surficial-geologic and landslide map of Vega Reservoir and vicinity, Mesa County, Colorado: Colorado Geological Survey Open-File Report 88-1, 2 pl., scale 1:24,000.

Srivastava, K.N., and Agarwal, A.N., 1975, Beas-Sutlej link project, Himachal Pradesh, *in* Engineering geology case histories: Geological Survey of India Miscellaneous Publication 29, part 1, p. 96–106, part 2, pl. 30.

Stapledon, D.H., 1967, Geological investigations at the site for the Kangaroo Creek Dam, South Australia: Institution of Engineers Civil Engineering Transactions, Australia, v. CE9, p. 31–43.

Staples, L.W., 1964, Landslide at north abutment of Lookout Point Dam, Oregon, *in* Trask, P.D., ed., Engineering geology case histories: Geological Society of America, no. 1, p. 3–48.

Stoffel, K.L., Joseph, N.L., Waggoner, S.Z., Gulick, C.W., Korosec, M.A., and Bunning, B.B., 1991, Geologic map of Washington—northeast quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-39, scale 1:625,000.

Stratton, J.H., 1938, The engineering features of the Conchas Dam project: Boston Society of Civil Engineers Journal, v. 25, p. 497–515.

Stroman, W.R., Beene, R.R.W., and Hull, A.M., 1984, Clay shale foundation slide at Waco Dam, Texas, *in* Prakash, S., ed., Proceedings: International Conference on Case Histories in Geotechnical Engineering, University of Missouri-Rolla, May 6–11, p. 579–586.

Subcommittee on Dam Incidents and Accidents, 1988, Lessons from dam incidents, USA-II: American Society of Civil Engineers, Committee on Dam Safety, U.S. Committee on Large Dams, 222 p.

Swanson, D.A., Anderson, J.L., Bentley, R.D., Byerly, G.R., Camp, V.E., Gardner, J.N., and Wright, T.L., 1979, Reconnaissance geologic map of the Columbia River Basalt Group in eastern Washington and northern Idaho: U.S. Geological Survey Open-File Report 79-1363, sheet 6, scale 1:250,000.

Tabor, R.W., Waitt, R.B., Jr., Frizzell, V.A., Jr., Swanson, D.A., Byerly, G.R., and Bentley, R.D., 1982, Geologic map of the Wenatchee 1:100,000 quadrangle, central Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1311, scale 1:100,000.

Tabor, R.W., Frizzell, V.A., Jr., Booth, D.B., and Waitt, R.B., 2000, Geologic map of the Snoqualmie Pass 30′×60′ quadrangle, Washington: U.S. Geological Survey Geologic Investigations Series I-2538, scale 1:100,000.

Takemura, K., Shimomura, M., Matsumoto, N., and Yamaguchi, Y., 1991, Behaviors of foundations for fill dams during construction and first filling of reservoirs in Japan, *in* Transactions: 17th International Congress on Large Dams, International Commission on Large Dams, Vienna, June 17–21, v. 3, p. 455–475.

Taniguchi, T., 1967, Landslides in reservoirs, *in* Proceedings: Jerusalem Academic Press, 3rd Asian Regional Conference on Soil Mechanics and Foundation Engineering, Haifa, September 25–28, v. 1, p. 358–361.

Taylor, G.M., Mahooty, D., and Rayssiguier, J., 2001, Historic dam—modern upgrade, *in* The future of dams and their reservoirs: 21st Annual USSD Lecture Series, United States Society on Dams, Denver, July 30–August 3, p. 165–176.

Terzaghi, K., 1960a, Report on the proposed storage dam south of Lower Stillwater Lake on the Cheakamus River, B.C., *in* Bjerrum, L., ed., From theory to practice in soil mechanics I—selections from the writings of Karl Terzaghi: New York, Wiley, p. 395–408.

Terzaghi, K., 1960b, Storage dam founded on landslide debris: Boston Society of Civil Engineers Journal, v. 47, p. 64–94.

Terzaghi, K., 1962, Dam foundation on sheeted granite: Géotechnique, v. 12, p. 199–208.

Thomas, H.H., 1976, The engineering of large dams: Sydney, Wiley, Part I, 376 p.

Tilford, N.R., and Sullivan, J.G., 1981, Lewis River hydroelectric developments, *in* Geology in the Pacific Northwest: Association of Engineering Geologists Field Trip Guidebook, 24th Annual Meeting, Portland, Oregon, September–October, p. 156–185.

Tolmachev, L.V., 1994, Effect of main engineering-geological factors on selection of sites of large dams, *in* Proceedings: 7th International Congress, International Association of Engineering Geology, Lisbon, September 5–9, v. 2, p. 1,267–1,273.

Tom, E.C.K., Mirafuente, N.T., and Estrella, E., 1976, A stability study of a concrete arch dam rock abutment, *in* Rock engineering for foundations and slopes: Proceedings of a specialty conference, Boulder, Colo., August 15–18, v. 1, p. 264–282.

Torner, V., and Novosad, S., 1991, The effects of difficult foundation conditions on the conceptual solution and construction of the Slezska Harta Dam, *in* Transactions: 17th International Congress on Large Dams, International Commission on Large Dams, Vienna, v. 3, p. 719–729.

Tweto, O., Moench, R.H., and Reed, J.C., Jr., 1978, Geologic map of the Leadville 1°×2° quadrangle, northwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-999, scale 1:250,000.

Vargas, M., 1971, Effectiveness of cut-offs under three earth dams, *in* Proceedings: 4th Panamerican Conference on Soil Mechanics and Foundation Engineering, San Juan, P.R., June, v. 2, p. 257–273.

Varnes, D.J., 1978, Slope movement types and processes, *in* Schuster, R.L., and Krizek, R.J., eds., Landslides—analysis and control: National Research Council, Washington, D.C., Transportation Research Board Special Report 176, p. 11–33.

Venzin, C., 1985, Rhodannenberg (Klöntal), *in* Swiss dams—monitoring and maintenance: Swiss National Committee on Large Dams, Edition for 15th International Congress on Large Dams, International Commission on Large Dams, Lausanne, June 24–28, p. 56–61.

Vichas, C., Skourtis, C., and Stiros, S., 2001, Kinematics of a landslide over the Polyphyton Reservoir (Greece), *in* Proceedings: 10th FIG (International Federation of Surveyors) Symposium on Deformation Measurements, Orange, Calif., March 19–22, p. 71–74.

Von Thun, J.L., 1985, San Luis Dam upstream slide, *in* Proceedings: 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, August 12–16, v. 5, p. 2,593–2,598.

Von Thun, J.L., 1987, Case studies of landslides and control measures, *in* Proceedings: 5th International Conference and Field Workshop on Landslides, Christchurch, August 1–12, p. 69–77.

Wahlstrom, E.E., 1974, Dams, dam foundations, and reservoir sites: Amsterdam, Elsevier, 278 p.

Wahlstrom, E.E., and Nichols, T.C., Jr., 1969, The morphology and chronology of a landslide near Dillon Dam, Dillon, Colorado: Engineering Geology, v. 3, p. 149–174.

Walker, F.C., and Harber, W.G., 1961, Design of the Trinity Dam, an earthfill structure 537 feet high, *in* Transactions: 5th International Congress on Large Dams, International Commission on Large Dams, Paris, May–June, v. 2, p. 743–748.

Walsh, T.J., Korosec, M.A., Phillips, W.M., Logan, R.L., and Schasse, H.W., 1987, Geologic map of Washington—southwest quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-34, scale 1:625,000.

Walters, R.C.S., 1971, Dam geology (2nd ed.): London, Butterworth's, 470 p.

Wang, F.W., Matsumoto, T., and Okuno, T., 2003, The deformation style and affecting factors of the giant Jinnosuke-dani landslide, Japan, *in* Bobrowsky, P.T., and Delzeit, R., eds., Program and extended abstracts volume: 2nd Annual Meeting, Board of Representatives, International Consortium on Landslides, Vancouver, BC, October 28–November 1, p. 49–50.

Watanabe, K., 1985, Foundation grouting of Ohuchi Dam, *in* Transactions: 18th International Congress on Large Dams, International Commission on Large Dams, Lausanne, June 24–28, v. 3, p. 535–552.

Weaver, K., 1989, Some geologic considerations for dam foundation grouting, *in* Proceedings: 7th Annual Meeting, Association of State Dam Safety Officials, New Orleans, October, p. 33–38.

Wentworth, C.K., 1929, The geology of dam sites, *in* Geology and engineering for dams and reservoirs: American Institute of Mining and Metallurgical Engineers Technical Publication 215, p. 78–96.

Weston, R.M., and Jacobs, R., 1997, Golden Cross—technical implications of owning a moving dam, *in* Proceedings of Technical Groups: New Zealand Society on Large Dams, v. 23, issue 2, p. 63–75.

Whipple, J.W., 1992, Geologic map of Glacier National Park, Montana: U.S. Geological Survey Miscellaneous Investigations Series Map I-1508-F, scale 1:100,000.

Widmann, B.L., and Miersemann, U., 2001, Geologic map of the Georgetown quadrangle, Clear Creek County, Colorado: Colorado Geological Survey Open-File Map 01-5, scale 1:24,000.

Willis, B., 1928, Report on the geology of St. Francis damsite, Los Angeles County, California: Western Construction News, June 25, v. 3, no. 12, p. 409–413.

Wilshusen, J.P., and Wilson, D., 1981, Tioga-Hammond flood control project, *in* Geology of Tioga and Bradford Counties, Pennsylvania: Guidebook for the 46th Annual Field Conference of Pennsylvania Geologists, Wellsboro, Pa., October 2–3, p. 77–90.

Wise, W.S., 1961, The geology of the Wind River area, Washington, and the stability relations of celadonite: Baltimore, Md., Johns Hopkins University, Ph.D thesis, 258 p.

Yeend, W.E., 1969, Quaternary geology of the Grand and Battlement Mesas area, Colorado: U.S. Geological Survey Professional Paper 617, 50 p.

Yeend, W.E., 1973, Slow-sliding slumps, Grand Mesa, Colorado: The Mountain Geologist, v. 10, no. 1, p. 25–28.

Yesenov, U.Ye., and Degovets, A.S., 1979, Catastrophic mudflow on the Bol'shaya Almatinka River in 1977: Soviet Hydrology—Selected Papers, v. 18, no. 2, p. 158–160.

Yesenov, U.Ye., and Degovets, A.S., 1982, Protection of the city of Alma-Ata from mud-rock flows, *in* Sheko, A., ed., Landslides and mudflows—Reports of Alma-Ata international seminar: Alma-Ata, October 1981, Centre of International Projects, GKNT, Moscow, p. 454–465.

Záruba, Qu., 1965, Geology of the Orlik Dam site: Water Power, July, p. 273–279.

Záruba, Qu., 1974, Importance of Quaternary events for the geological conditions of building sites, *in* Centenaire de la Société Géologique de Belgique Colloque Géologie de L'Ingénieur: Liege, September 9–13, p. 259–272.

Záruba, Qu., 1979, The importance of slope movements in dam construction: International Association of Engineering Geology Bulletin 20, p. 158–162.

Záruba, Qu., and Mencl, V., 1976, Engineering geology: Amsterdam, Elsevier, 504 p.

Záruba, Qu., and Mencl, V., 1982, Landslides and their control: Amsterdam, Elsevier, 324 p.

Zhang, X., Liu, T., Wang, Y., and Luo, J., 1985, The main features of debris flows and control structures in Hunshui Gully, Yunnan Province, China, *in* Proceedings: International Symposium on Erosion, Debris Flow and Disaster Prevention, Tsukuba, Japan, September, p. 181–186.

Zingg, W., 1964, Castiletto, *in* Behavior of large Swiss dams: Swiss National Committee on Large Dams, p. 285–295.

Published in the Central Region, Denver, Colorado
Manuscript approved for publication February 24, 2006
Page layout and cover design by Sharon M. Powers

Appendix

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references.

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
Algeria/ none/ 36.48N, 5.27E	Iril-Emda/ Agrioun River	Rockfill/ Hydroelectric	1954/ Government power company	76/575	160	Slide in schist	Left abutment	Rockfill dam substituted for concrete dam because of slide. “Dam built on a sliding section and in this case the dam “supports” landslide and drainage facilities are provided to raise up the stability.” (Tolmachev, 1994)	Lordet and others (1955), Tolmachev (1994)/None
Algeria/ Skikda/ 36.59N, 6.90E	Zardezas/ Saf-Saf River	Concrete gravity/ Irrigation	1948/ Federal government	64/242	31	Slide in sandstone	Left abutment	During construction, 100,000-m^3 slide occurred in sandstone left abutment. Left end of dam was moved downstream to stable limestone body. Cylindrical wall was built in slide mass to allow construction of left part of dam. In 1970, dam height was raised from 40 m to 64 m. Part of the new dam rests on this cylindrical wall, and thus was built over the landslide. Stability of the new dam ensured by 500-ton anchor cables.	Gignoux and Barbier (1955, p. 92), Walters (1971, p. 313), International Commission on Large Dams (1974, p. 455), Tolmachev (1994)/ Christophe Bonnard (oral commun., 2004)
Argentina/ San Juan/31.5S, 8.7W	Quebrada de Ullum/San Juan River	Earthfill/ Irrigation, hydro-electric, flood control	1981/ Provincial government	60/300	440	Rock slide	Right abutment	Bedding-plane slips at contacts between sandstone and claystone were probably caused by tectonic folding. However, during construction a 260,000-m^3 rock slide occurred adjacent to the right abutment causing partial obstruction of the diversion channel. Remedial measures: (1) buttress at toe of slide, (2) debris removed from river bottom, (3) excavation slope flattened, (4) grout curtain, (5) two rows of drains installed in right bank downstream of the dam.	Pronsato and others (1973), Figueroa and others (1976)/None
Australia/ South Australia/ 34.87S, 138.78E	Kangaroo Creek/ Torrens River	Rockfill/ Water supply, flood control	1969/ Government	64/131	19	Slides, boulders, loose slabs	Both abutment areas	In dam-site area, there are scars of two slides on left bank and one on right. Slides are “block-slide” type. Also, some scree and boulders. Because of slides, dam design changed from arch to rockfill. Most of slide material probably removed during construction, but some remains.	Stapledon (1967)/ None
Australia/ Victoria/ 37.70S, 145.82E	O’Shannassy/ O’Shannassay River	Earthfill with reinforced concrete core wall/ Water supply	1928/ Municipal government	34/226	4.2	Debris slide	Right abutment	Right end of dam abuts extensive area of landslide debris (colluvium). Shears and slickensided surfaces were found in undisturbed samples of landslide debris. Concrete corewall was taken to bedrock.	Fell and others (1992, p. 174), Fell and others (2000)/consultant’s report; reports of Melbourne and Metropolitan Board of Works.

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
Australia/ Tasmania/ 41.66S, 146.22E	Parangana/ Mersey River	Rockfill/ Hydroelectric	1968/ Hydroelectric commission	53/189	15	Thick debris-avalanche deposits in valley, talus on slopes	Foundation and both abutments	Thick (>50 m) debris-avalanche deposits associated with glacial advance form part of foundation. Talus forms part of surface of both abutments. Talus removed under dam core on both abutments. Talus fairly impermeable; however, extensive cement-grout fan through talus was included in design of both abutments.	Paterson (1971), Thomas (1976, p. 156), Fell and others (1992, p. 140–141)/None
Australia/ Victoria/ 39.68.S, 145.29E	Sugarloaf/ Sugarloaf Creek	Concrete-faced rockfill/ Water supply	1980/Rural water commission	85/ 1,050	100	"Old landslide"	Right abutment	Suspected old landslide on downstream right abutment confirmed by trenching. Minor down-dip movements at left abutment due to past undercutting by erosion.	Fell and others (1992, p. 67–70)/None
Australia/ Victoria/ 37.85S, 146.40E	Thomson/ Thomson River	Rockfill/ Water supply, irrigation	1983/Rural water commission	166/ 1,170	1,122	Dip-slope slides	Both abutments, right most serious	Most of slides in sedimentary rocks were removed during construction. Remaining disturbed rock stabilized by 2.6-million-m^3 rockfill buttress.	Hunter (1982), Fell and others (1992, p. 70–72)/ None
Australia/ Victoria/ 36.06S, 148.27E	Tooma/ Tooma River	Earthfill-rockfill/ Hydroelectric	1961/ Hydroelectric authority	67/305	28	Sliding on joints in granite	Both abutments, right the most serious	Because past slope movements were not recognized before construction, there was extra cost for (1) rockfill buttresses, (2) dental work on open joints, (3) addition of downstream grout curtain, and (4) rezoning of embankment.	Hunter (1982), Fell and others (1992, p. 59–64)/ None
Australia/ Western Australia/ 32.20S, 116.06E	Wungong/ Wungong Brook	Earthfill–rockfill/ Water supply	1979/City water corporation	65/460	60	Landslide	Right abutment	During construction, landslide was reactivated. Stabilized by addition of rockfill buttress. Filter blanket placed over slide materials that were left in place under the rockfill.	Lilly (1986), Fell and others (1992, p. 64-67)/None
Austria/ Tyrol/47.23N, 12.10E	Durlassboden/ Gerlosbach	Earthfill/ Hydroelectric	1966/Electric power company	83/470	53.5	Rock slide overlying talus	Right abutment	Right abutment consists of a large block of graphitic schist and quartzite that had slid down valley wall into valley deposits of glaciofluvial sands and gravels and lacustrine silts. Foundation and abutment sealed by double-row grout curtain extended 50 m into valley sediment.	Kropatschek and Rienössl (1967), Záruba (1974), Rienössl and Schnelle (1976), Simmler (1977, p. 132–138), Záruba and Mencl (1982, p. 242–243), Austrian National Committee on Large Dams (1991, p. 191–194)/None

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
Austria/ Tyrol/47.12N, 11.87E	Eberlaste (Stillup)/ Zemm River tributary	Earthfill/ Hydro-electric	1968/ Electric power company	28/480	8.2	Rock fall (talus)	Sides of foundation	Foundation is talus interfingered with alluvium. Asphalic-concrete impervious core continuous with slurry-trench cutoff into talus/alluvium to depth of 52 m. In addition, ~50-m-wide stabilizing fill was built as a buttress at downstream toe of dam.	Rienössl and Schnelle (1976), Simmler (1977, p. 143–148), Austrian National Committee on Large Dams (1991), Leobacher (2000)/None
Austria/ Carinthia/ 46.52N, 14.47E	Freibach/ Drau River tributary	Rockfill/ Hydro-electric	1958/Electric power company	41/150	5.5	Rock slide in limestone	Left abutment	Concrete diaphragm constructed through slide. During reservoir filling, diaphragm leaked. Grout curtain added, but leaked. Second grout curtain successfully added, supplemented by sealing with chemical materials.	Simmler (1977, p. 109–114)/None
Austria/ Tyrol/46.95N, 10.75E	Gepatsch/ Faggenbach River	Rockfill/ Hydro-electric	1965/Electric power company	153/600	140	Rock fall (talus)	Left abutment	"On the left slope the rock is covered with a layer of talus and redeposited boulder clay up to 25 m thick" (Lauffer and Schober, 1964). "Mass movement was seen to occur on the left valley slope already during first partial filling. Thorough investigation and model studies proved this to be the reactivation of an old rock slide" (Simmler, 1977, p. 120). Apparently, the only material removed was in the upstream zone of the dam foundation/left abutment.	Lauffer and Schober (1964), Schober (1970), Simmler (1977, p. 120–124)/None
Bolivia/Tarija/ 21.7S, 64.8W	San Jacinto/ Tolomosa River	Concrete arch/ Irrigation, hydro-electric, recreation	Under construction (1998)/ Electric power consortium	49/100	54.3	Wedge failure, topple	Left abutment	Landslide in slate, sandstone, and overlying lacustrine sediments is one of several along left valley wall. Reactivated during construction. Left abutment rebuilt by filling adits with concrete.	Riemer (1995)/W. Riemer (written commun., 1998)
Brazil/ Paraíba/6.89S, 38.39W	Engenheiro Avidos (Piranhas)/ Piranhas River	Zoned rockfill/ Irrigation, water supply, flood control	1936/Federal government	47/359	255	Block slump, talus	Both abutments	Right abutment is weathered-gneiss block slump; left abutment is talus. Both are fairly impervious; however, toe-drain system was installed on each abutment.	DNOCS (1982, p. 58–65)/None

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
Brazil/Sao Paolo/ 21.60S, 46.95W	Euclides da Cunha/ Pardo River	Earthfill/ Hydroelectric	1960 (rebuilt 1977)/Electric power company	92/312	13.4	"Ancient landslides"	Both abutments	"Ancient landslides" in form of clayey "residual talus" found at both abutments. Cutoff trenches filled with impervious soil were placed through talus, followed by grout curtains placed through the trenches. Dam failed at right end in 1977 due to flood overtopping. Slide material at right abutment may have been factor.	Vargas (1971), Brazilian Committee on Large Dams (1982, p. 411–435)/None
Bulgaria/Plovdiv/ 42.04N, 24.47E	Krichim/ Vacha River	Concrete buttress-gravity/ Hydroelectric	1972/ Government	105/269	18	Rock slide	Right abutment	"Ancient" rock slide (80 m thick; total volume: 10.5 million m^3) in gneiss and marble extends along the valley wall from 500 m above dam to river bottom.	Demirev (1979)/None
Canada/ British Columbia/ 49.98N, 123.15W	Cheakamus/ Cheakamus River	Earthfill-rockfill/ Hydroelectric	1957/ Electric power company	28/683	52.4	Debris avalanche–debris flow	Most of foundation	Foundation is "Rubble Creek Wash," a debris avalanche–debris flow that occurred in 1855–56. Permeability and stability of this material were studied before construction. Dam has functioned well. Greatest hazard may be slight possibility of another avalanche–flow occurrence, sending wave over top of dam.	Terzaghi (1960a, b), Moore and Mathews (1978), Eisbacher (1983), Legget and Karrow (1983, p. 23–14 to 23–15), Evans and Savigny (1994)/None
Canada/ Saskatchewan/ 51.27N, 106.88W	Gardiner/ South Saskatchewan River	Earthfill/ Irrigation, water supply, hydroelectric	1968/ Provincial government	69/5090	9,867	Massive slump in shale	Left-abutment area	Large-scale prehistoric slide in shale of left abutment. Local failure during construction led to removal of much of unstable shale under central zone of dam. Extensive berms added and abutment slopes flattened.	Ringheim (1964), Jaspar and Peters (1979), Peters and Long (1981)/ None
Canada/Quebec/ 50.9N, 66.9W	Sainte Marguerite-3/Sainte Marguerite River	Earthfill-rockfill/ Hydroelectric	1998/Electric power company	171/378	Not known	Rock fall (talus) and rock slide	Left abutment, left foundation, right abutment	Core of dam is in excavation to gneiss bedrock. Under left dam shell, talus was considered to be acceptable as foundation and was not removed. Large right-abutment slide mass mostly left in place during construction; mass settled <15 cm under weight of >40 m of fill.	Rattue and others (1999, 2000)/Interview with consultant

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
Canada/British Columbia/ 49.44N, 122.97W	Seymour Falls/ Seymour River	Earthfill-concrete/ Water supply	1961/City water district	30/457	25.3	Debris-flow cone	Right abutment	Debris-flow cone from tributary stream forms right abutment of embankment dam. Impervious upstream blanket prevents seepage through debris cone.	Ripley and Campbell (1963), Heidstra and others (1995)/None
Chile/VII Region/ 36.17S, 71.25W	Bullileo/ Bullileo River	Earthfill/ Irrigation	1949/ Irrigation association	70/260	60	"Great slide"	Left abutment	Very large slide in moraine deposits forms left abutment. Dam has had piping problems in moraine of right abutment (1982), but no difficulty with left abutment.	Castro and Garces (1985)/L. Valenzuela (oral commun., 1996)
Chile/V Región (Valparaíso)/ 32.97S, 70.25W	Los Leones/ Los Leones Stream	Earthfill/ Mine tailings disposal	1998 (final stage)/ Mining company	160/500	Not known	Debris slide, earth slide	Right abutment	Slide not recognized originally; however, it has had no effect on dam performance. Thus, no remedial measures installed.	None/L. Valenzuela (written commun., 1996)
Chile/Santiago Metropolitan Region/ 33.65S, 70.08W	Yeso/Yeso River	Earthfill/ Water supply	1967/Local government	61/350	250	Debris flow and rock fall	Both abutments (?)	Unacceptable seepage through both abutments. Extensive cement grouting in 1979–81. Debris-flow materials probably also present in foundation.	Moreno and others (1991)/L. Valenzuela (written commun., 1996)
China/Yunnan/ 26.25N, 103.15E	Hunshui Gully debris-retention dam #4/Hunshui Stream	Stone and concrete/ Debris retention	1978–81(?)/ District government	16/Not known	Not known	Debris flow	Entire foundation	Debris-retention dam #4 is one of a series built from 1978 to about 1981 to retain debris-flow deposits in Hunshui Gully. Present status not known.	Li and Luo (1981), Zhang and others (1985)/None
China/Anhui/ 31.66N, 115.88E	Meishan/ Shihe River	Concrete multiple arch/ Flood control, irrigation, hydroelectric	1956/ Government	88/443	2,275	Rock slide along joints in granite	Right abutment	In 1962, movement occurred along joints in right abutment. Apparently, these joints had shown some movement before construction. Remedial measures: (1) grout curtain, (2) impervious membrane upstream of right abutment, (3) anchors, and (4) buttresses.	Qi (1986), Chinese National Committee on Large Dams (1987, p. 134–138)/None

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
China/Yunnan/ near Sichuan border	Wuping/ Papa River	Rockfill/ Hydroelectric	Under construction/ Government	49/215	49.9	Earth slide	Right end of foundation	Slide deposit (volume: 1.2 million m^3) is in right end of foundation. Remedial measures: (1) 14-m-high rockfill platform constructed on slide as preload, (2) vertical rock piles inserted through slide deposit.	Chen and others (2001)/ Chinese engineers
Cyprus/Limassol/ 34.72N, 32.99E	Polemidhia/ Garyllis River	Earthfill/ Irrigation	1965/ Government	45/196	3.9	Rock slide, rock fall	Left abutment	Left abutment consists of limestone and chalk rock slide–rock fall blocks. Permeability of landslide material led to installation of grout curtain.	Konteatis (1974, p. 202–208)/None
Czech Republic/ South Moravia/ 49.12N, 16.16E	Dalešice/ Jihlava River	Rockfill/ Hydroelectric, water supply, irrigation	1979/ Government	100/330	127.3	Rock slide	Right abutment	Construction caused 150,000-m^3 reactivation of rock slide in amphibolite zone of right abutment. Slide stabilized by (1) rockfill buttress at toe of slope, (2) unloading of upper part of slide, and (3) use of rock anchors.	Mencl (1977), Hrdy and Mares (1978), Záruba (1979), Záruba and Mencl (1982, p. 245–246), Hobst and Zajíc, (1983, p. 399–401)/S. Novosad (written commun., 1996)
Czech Republic/ North Bohemia/ 50.36N 13.42N	Nechranice/ Ohre River	Earthfill/ Flood control, hydroelectric, irrigation, recreation, water supply	1968/ Government	52/ 3,280	287.6	Slides in claystone	Right abutment	Pleistocene bank erosion had caused slides to depth of 15 m in claystone of right abutment. Angle of slope immediately upstream of right abutment flattened to increase stability. Impervious clay-cement cutoff installed though right abutment to reduce seepage.	Grosman and Lejsek (1965), Czechoslovak National Dam Committee (1967, p. 31), Horský and Spanilá (1997)/None
Czech Republic/ North Moravia/ 49.90N, 17.57E	Slezska Harta/ Moravice River	Rockfill/ Water supply, flood control	1997/ Government	65/540	217.5	“Ancient” slides in shale and basalt	Both abutments	During construction, movement occurred in shale slide of left abutment and creep in basalt blocks of right abutment. Remediation: (1) excavation of upper left slope, (2) buttress at toe of left slope, and (3) surface/subsurface drainage.	Novosad (1990), Torner and Novosad (1991), Novosad and Novosad (1993)/None

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
Czech Republic/ North Moravia/ 49.77N, 18.52E	Terlicko/ Stonávka River	Earthfill/ Water supply, flood control	1962/ Government	28/617	24.4	Slide in clay shale	Right abutment	Right abutment is in toe of huge clay-shale slide. Chemical and cement grout curtains placed. Stability increased by construction of buttress on right side. Movement continues (as of 1996).	Czechoslovak National Dam Committee (1967, p. 28)/S. Novosad (written commun., 1996)
Czech Republic/ North Moravia/ 49.73N, 18.45E	Zermanice/ Lucina River	Concrete gravity/Water supply, flood control	1958/ Government	37/617	27.2	Slide in flysch	Right abutment	Slide of entire hillside of clay shales with layers of sandstone and weathered teschenite. Reactivated during construction. Right abutment continues to slowly deform by bulging.	Czechoslovak National Dam Committee (1967, p. 16)/S. Novosad (written commun., 1996)
Ecuador/Azuay/ 2.68S, 78.63W	Daniel Palacios (Amaluza)/ Paute River	Concrete arch-gravity/ Hydroelectric	1983/Federal government	167/420	120	Rock slide	Left abutment	Reactivation during construction; probably part of toe of large prehistoric slide in decomposed granodiorite. Remedial measures: (1) active part removed and (2) concrete beams with prestressed anchors placed at the abutment.	Tom and others (1976), Riemer (1995)/ W. Riemer (written commun., 1998)
Ecuador/Guayas/ 1.0S, 79.8W	Daule Peripa/ Daule River	Earthfill/ Irrigation, flood control, water supply, hydroelectric	Uncertain (under construction in 1988)/ Government	78/246	6,000	Small shale slide due to stress relief	Right abutment	Reactivation of slide during construction. Blocks of tuffaceous sediments slid on sheared shale layer. Cracks were filled with concrete and additional filters were placed.	None/W. Riemer (written commun., 1998)
France/ Corrèze/ 45.41N, 2.49E	Bort/ Dordogne River	Concrete gravity arch/ Hydroelectric	1951/ Hydroelectric company	131/390	477	Bedding plane slips in gneiss and schist	Both abutments	Bedding-surface slips formed weak clay layers between gneiss and underlying schist beds. During construction, a slide of several thousand cubic meters occurred in left abutment; slide area was bridged by concrete arch. Right abutment: zone of crushed material removed and replaced by reinforced concrete.	Walters (1971, p. 193–200)/None

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
France/Basse Alps/ 43.85N, 6.54E	Chaudanne/ Verdon River	Concrete thin arch/ Hydroelectric	1952/ Federal government hydroelectric company	71/95	16	Rock slide on joints	Right abutment	During construction, a limestone block (vol. ~1,200 m^3) broke off along steeply-dipping, pre-existing fault, and was removed. Another 4,000 m^3 was stabilized by rock anchors, concrete buttress, and cement grout.	Haffen (1955), Walters (1971, p. 139–140), Anderson and Trigg (1976, p. 31–32), Hobst and Zajíc (1983, p. 405–406)/None
France/Hautes Alpes/ 44.46N, 6.24E	Serre-Ponçon/ Durance River	Earthfill/ Hydroelectric, irrigation	1960/ Electricité de France	129/600	1.2	Talus (scree)	Both abutments and foundation	Large deposit of talus interbedded with alluvium was left in place in foundation of right end of dam. Seepage prevented by injection of impervious cutoff to bedrock. 500,000 m^3 of scree removed from left abutment.	Ischy and Haffen (1955), Cabanius and Maigre (1958)/None
Greece/ Sterea Hellas/ 38.66N, 21.87E	Evinos/ Evinos River	Earthfill/ Water supply	1998/ Government	124/640	113	Slide in colluvium and weathered flysch	Just above left abutment	Abutment excavation reactivated part of large slide in left abutment immediately upstream from spillway entrance, barely in contact with dam. Remedial measures: (1) pumping wells, (2) replacing part of sliding surface with free-draining material, and (3) removing part of upper slide.	Dounias and others (1996)/None
Greece/Fokis/ 38.53N, 22.12E	Mornos/ Mornos River	Earthfill/ Water supply	1979/ Government	126/815	780	Rock slide	Right abutment	Pleistocene rock slide (vol. ~25 million m^3) is at right end of dam. Dam acts as buttress, and toe buttress (8 million m^3) was installed along reservoir shore.	Schetelig (1989), Riemer (1995)/W. Riemer (written commun., 1998)
Greece/West Macedonia/ 40.30N, 22.10E	Polyphyton/ Aliakmon River	Rockfill/ Hydroelectric	1974/ Government	112/640	1,939	Slide in colluvium and gneiss	Both abutments	Several slides in area. Left-bank downstream slide barely contacts toe of dam. Alexis slide (20 million m^3) lies directly above right abutment but is not in contact with dam because design was adjusted to remove vital structures from slide area. Surface drains and drainage adit added.	Riemer (1995), Riemer and others (1996), Vichas and others (2001)/W. Riemer, (written commun., 1998)

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
Greece/East Macedonia/ 41.3N, 24.3E	Thissavros/ Nestos River	Rockfill/ Hydroelectric	1986/ Government	170/480	705	Slide in gneiss	Not known	During excavation, slide reactivation occurred. Part of dam sits on slide mass in gneiss. Extensive remediation installed. Currently, no indication of movement.	Krapp and Pantzartzis (1989), Riemer (1995)/W. Riemer (written commun., 1998)
India/ Uttar Pradesh/ 30.6N, 77.8E	Ichari/ Tons River	Concrete gravity/ Hydroelectric	1975/State government	59/155	14.3	Slide in slates and quartzites	Left abutment	Depth of slide debris in left abutment was 33–63 m. To stabilize left abutment: (1) reinforced concrete cutoff wall tied to sound quartzite band and (2) 45-m-long concrete diaphragm ties dam to sound rock.	Jalote and others (1975), Lavania (1988)/None
India/West Bengal/ 27.1N, 88.9E	Jaldhaka Stage I/ Jaldhaka River	Diversion wier/ Hydroelectric	1967/State government	18/98	Not known	Rock and debris slides in schist and gneiss	Right abutment	"Huge rock-cum-debris slides occurred from the right abutment during the 1964–66 monsoons, covering the partly constructed intake structure" (Roy, 1975). Remedial measures: (1) abutment was "dressed" and benched at suitable intervals, (2) retaining and "breast" walls were constructed to prevent further slides, and (3) slide area was grouted.	Roy (1975), Chatterjee (1979)/None
India/Himachal Pradesh/ 31.80N, 76.95E	Pandoh/ Beas River	Earthfill-rockfill/ Irrigation, hydroelectric	1977/ Federal government	76/411	41	Slump mass and shear zone in phyllite	Both abutments	Proposed concrete dam changed to rockfill because of slump mass (right abutment) and shear zone (left abutment). Shear zone excavated to 3-m depth; trench backfilled with impervious material. Right axis of dam moved upstream to prevent failure into reservoir. Prevention measures: (1) 15-m-deep concrete cutoff through slump, (2) horizontal-drain system, and (3) buttressing by dam.	Srivastava and Agarwal (1975)/ None
India/Himachal Pradesh/ 31.98N, 75.94E	Pong/ Beas River	Earthfill/ Irrigation, hydroelectric	1974/State government	133/ 1,950	8,570	Block glide in clay shale	Left abutment	Large, inactive slide in left abutment in vicinity of tunnel intakes. Many open cracks ("glide cracks"). Remedial measures: (1) shallow unsound rock removed from core foundation, (2) concrete caissons installed as "keys," and (3) toe buttresses installed at river level.	Bhatnagar and Parkash (1967), Jalote and Tikku (1975), Central Board of Irrigation and Power (1979, p. 183–235)/None

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
India/Rajasthan/ 24.93N, 75.56E	Ranaptrap Sagar/ Chambal River	Masonry/ Irrigation, hydroelectric	1967/State government	58/ 1,143	290	Slumps in shale	Left abutment	Deep-seated slumping in shale and cracking in sandstone. Remedial measures: (1) flattening slopes, (2) clay blankets with filters, (3) area grouting, (4) anchors, (5) retaining wall, and (6) drainage.	Sanganeria (1975)/None
India/Jammu and Kashmir/ ~32.8N, 74.8W (near Dyangarh)	Salal/ Chinab River	Rockfill/ Hydroelectric	1986/State government	118/630	1.5	Deep-seated rock slump in dolomite	Right abutment	"...the right abutment…has a deep seated huge slump of rock overlain by thick cover of overburden" (Sen and others, 1987). Treatment of abutment: (1) removal of slump mass in core contact area, (2) areal and curtain grouting, (3) concrete cutoff, and (4) "wrap around" of core material covering the slump zone.	Sen and others (1987)/ None
Iran/Khuzestan/ 32.3N, 48.9E	Upper Gotvand/ Karun River	Rockfill/ Hydroelectric	Under construction (2004)/ Government power company	170/760	4,500	Right abutment: rock topple; left abutment: rock slide	Both abutments	Both abutments include dislocated rock masses in Bakhtyari Fm. (conglomerate). Right abutment mass apparently is a rock topple; dislocated left-abutment mass is a rock slide.	None/Consultants
Italy/Sicily 37.83N, 14.58E	Ancipa/ Troina River	Cellular concrete gravity/Irrigation, hydroelectric	1953/Government	105/253	30.4	Thick talus	Foundation and right abutment	"…bottom and right shoulder are covered with talus." Concrete diaphragm 4 m thick sunk through talus to bedrock at right abutment.	ANIDEL (1961, v. 1, p. 304–306)/None
Italy/Val D'Aosta/ 45.63N, 7.06E	Beauregard/ Dora di Valgrisenche	Concrete arch-gravity/ Hydroelectric	1960/Government	132/394	74	Slide in schist	Left abutment	Large slide in mica schist moved onto alluvium. During first filling of reservoir the landslide accelerated, attaining a displacement rate of 20 mm/month producing cracks in lower third of the dam. Glaciofluvial sediments from deep pocket under slide had to be replaced by concrete. Also, water-tight membrane placed by cement injection.	ANIDEL (1961, v. 1, p. 313–315), Desio (1973, p. 99–101), Záruba (1974), Záruba and Mencl (1982, p. 243–244), Picarelli and Russo (2004))/None

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
Italy/Umbria/ 43.16N, 12.60E	Casanuova/ Chiascio River	Earthfill/ Irrigation, water supply	1994/Irrigation district	88/444	224	Translational slide	Right abutment	Slide is 70–80 m thick. Water level increase in reservoir during construction (1991) caused 20-million-m^3 slide reactivation. Remedial measures: (1) reduced rate of reservoir filling and (2) installed physical remediation.	Catalano and others (2000), Picarelli and Russo (2004)/ Italian National Dam Service
Italy/Reggio Emilia/ 44.29N, 10.37E	Ozola/Ozola River	Concrete multiple arch/ Hydroelectric	1929/Government	25/96	0.061	Slide in thick talus	Left abutment	Concrete cutoff at left abutment was sunk through 39.5 m of talus by means of superimposed tunnels.	ANIDEL (1961, v. 7, p. 76–88)/None
Italy/Trentino A. Adige/ 46.30N, 10.68E	Pian Palù/ Noce Torrent	Concrete blocks/Hydroelectric	1959/Government	52/180	16.1	Deep-seated slump	Left abutment	Deep-seated rotational slump (sackung?) in mica schist. To avoid consequences of possible movement of abutment, dam type was chosen consisting of concrete blocks separated by sand. Concrete cutoff wall placed to depth of 30 m in landslide debris of left abutment during construction.	ANIDEL (1961, v. 1, p. 18–19), Desio (1973, p. 899–900), Picarelli and Russo (2004)/None
Italy/Reggio Emilia/ 43.88N, 12.09E	Quarto sul Savio/Savio River	Concrete gravity/ Hydroelectric	1925/Government	21/59	6.67	Landslide in flysch	Left abutment	Dam was built partially on 1812 natural landslide dam derived from clayey sandstone. A few years after construction, problems occurred in operating gates of the dam.	ANIDEL (1953, v. 6, p. 234), Picarelli and Russo (2004)/ None
Italy/Modena/ 44.27N, 10.73E	Riolunato/ Scoltenna River	Concrete multiple arch/ Hydroelectric	1920/Government	27/90	0.06	“Mass-flow”	Right abutment	Monitoring from 1979–93 indicated total creep of right abutment of 17 cm toward the dam. There is no failure surface; therefore, authors classified movement as “flow.” Probably continuation of pre-dam movement.	Castelucci and others (1999), Picarelli and Russo (2004)/None

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
Italy/Sicily/ 37.96N, 13.37E	Rossella/ Rossella River	Earthfill/ Water supply, irrigation	1965/Irrigation district	27/336	17.2	Earthflow in clay shale	Left abutment	Pre-existing earthflow in flysch of the left abutment was reactivated during construction in 1961. In 1997–98, sudden reactivation again occurred causing cracks in cutoff wall at dam toe and displacements on dam crest. Remedial measure: lowering reservoir level. Monitoring program: inclinometers, piezometers, and topographic monuments.	Catalano and others (2000), Picarelli and Russo (2004)/ Italian National Dam Service
Italy/Tuscany/ 44.08N, 10.77E	Sperando (Tistino)/ Lima River	Concrete gravity/ Hydroelectric	1929/Government	34/112	0.4	Landslide	Left abutment	Lower half of left abutment consists of landslide deposits. Probably part of the 1818 Lizzano landslide. Apparently stable at present.	ANIDEL (1952, v. 5, p. 46–49)/ L. Ermini (oral commun., 1999)
Italy/Sicily/ 37.70N, 12.76E	Trinità/ Delia River	Earthfill/ Irrigation, water supply	Irrigation district/Not known	30/322	18	Earth flow–earthslide	Left abutment	Existence of earth flow–earth slide was known during construction. Thus, spillway was built on piles. In 1965 and 1981, landslide reactivated, damaging caretaker's house, but not dam or appurtenant structures. Landslide still active. Instrumentation is being added.	Catalano and others (2000)/Italian National Dam Service
Italy/Veneto/ 46.41N, 12.25E	Vodo/Boite River	Concrete domed-arch/ Hydroelectric	1960/Government	42/74	1.39	"Alluvial landslides"	Left abutment	Diaphragm, consisting of overlapped piles in reinforced concrete, contacts left abutment, which is described as "morainic materials and alluvial landslides." Bentonitic slurry aided excavation for diaphragm.	ANIDEL (1961, v. 1, p. 320)/None
Japan/Saitama/ 36 N, 139E	Futase/Ara River	Concrete arch/ Multipurpose, irrigation, hydroelectric	1962/Federal government	95/289	26.9	Slide	Left abutment	Slide in phyllite, sericite, and schist of the left abutment occurred during construction (mid-February 1958). Remedial measures: (1) piling, (2) underground drainage, and (3) a buttress. Dam was eventually completed.	Taniguchi, 1967/ None

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
Japan/Ishikawa/ 36.02N, 136.76E	Jinnosuke #5 sabo dam (new dam)/ Tedori River	Concrete gravity/Debris-flow retention	1925 (original dam)/ Government	22.5/ ~50	Not known	Deep-seated slide	Entire foundation	Largest of more than 50 sabo dams built on pre-existing slide (Jinnosuke-dani) in altered sandstone, shale, and rhyolite (entire gully is moving). The original Jinnosuke #5 dam (height:17 m) has moved about 5 m since 1925 and was recently rebuilt as New Jinnosuke #5. There are several other dams in the valley that are 10 m high or higher (notable: Jinnosuke #3,~18 m, and Jinnosuke #6,~13 m). Even though these dams are slowly moving, all are successfully performing their debris-retention function.	Fukuoka and Taniguchi (1961), Ohta and others (1996), Wang and others (2003), Okuno and others (2004)/M. Fukuoka (written commun., 1999)
Japan/Niigata/ 37.5N, 138.9E	Kassa/ Kassa River	Rockfill/ Hydroelectric	1978/Electric power company	90/487	13.5	Volcanic mudflow	Left abutment	Most of left abutment consists of "low-cemented volcanic mud-flow deposit." Entire foundation area subjected to shallow grouting (~1,500 m^3 of mortar). After grouting, top 2–3 m of mud flow was removed.	Japanese National Committee on Large Dams (1979, p. 26), Mikuni (1980)/ None
Japan/Tochigi/ 36.7N, 139.5E	Kawamata/ Kinu River	Concrete arch/ Flood control, hydroelectric, irrigation	1966/Federal government	117/137	87.6	Rock fractures and shear zones	Abutment	"….rock strata were permeated by fractures and failure zones, and could not be relied upon to take the stresses transmitted by the dam unless special measures were adopted" (Hobst and Zajíc, 1983, p. 392–394). Prestressed anchors were used to affix a load-distribution wall to the rock face.	Hobst and Zajíc (1983, p. 392–394)/None
Japan/ Fukushima/ 37.5N, 140.0E	Ouchi/ Ono River	Earthfill/ Hydroelectric	1988/Electric power company	102/340	18.5	Mud flow	Left abutment and left end of foundation	Pre-existing mud-flow deposit, derived from volcanic tuffs upstream, was removed at cutoff trench and partially moved upstream (replaced by rockfill). However, deposit was left in place beneath the downstream part of the dam.	Mikuni (1980), Kawashima and Kanazawa (1982), Watanabe (1985)/None
Japan/Tochigi/ 36.8N, 139.9E	Terayama/ Miya River	Rockfill/ Flood control, irrigation	1984/ Prefecture government	62/260	1.2	Rock fall (talus)	Right abutment	Surface of right abutment covered by talus. As remedial measure, talus layer was covered by an "earth blanket." Curtain grouting performed through lower end of blanket.	Takemura and others (1991)/ None

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
Kazakhstan/ None/ 43.16N, 76.90E	Debris-flow-retention dam/Bolshaya Alma-Atinka River	Cellular reinforced concrete/ Debris-flow retention	~1982/ Government	40/422	14.5	Debris flows	Foundation	This debris-flow-retention structure was built on pre-existing debris flows with no loss of function. It is meant to control debris flows that often occur on the Bolshaya Alma-Atinka River upstream from Almaty.	Yesenov and Degovets (1979, 1982), Sheko (1988), Popov (1999)/None
Kazakhstan/ None/ 43.20N, 76.99E	Medeo/ Malaya Alma-Atinka River	Earthfill/ Debris-flow retention	First dam: 1969; additional higher dam: ~1975–80/ Government	150/530	Useful retention capacity 12.6	Debris flows	Foundation	Original 110-m-high dam was built on debris-flow base as an explosives-charged “landslide” dam. “Reservoir” was nearly filled by 1973 debris flow. Additional height added after 1973 as a conventional earthfill dam. Dam serves function well; bedrock foundation is not needed.	Yesenov and Degovets (1979, 1982), Popov (1999)/None
Mexico/Durango/ 36.02N, 136.76W	Francisco Zarco (Las Tórtolas)/ Nazas River	Earthfill/ Irrigation, flood control	1969/ Government	40/480	438	Talus with landslide blocks	Both abutments	Talus deposits, as well as limestone blocks, are found on both abutments. Impervious slurry trench 3 m wide and 20 m deep constructed through these materials. A 3-line grout curtain was placed from bottom of trench.	Marsal and Reséndiz (1971), Secretaria de Recursos Hidráulicos (1976a, p. 96–125)/None
Mexico/Durango/ 24.61N, 103.31W	Los Naranjos/ Santa Clara River	Earthfill/ Irrigation, flood control	1985/ Government	48/542	26	Landslide in pyroclastic rocks	Right abutment	Original site exploration inadequate to detect pre-existing slide. Reactivation of 2-million-m^3 slide began in 1987. Immediate remediation: (1) controlled release of reservoir, (2) cement-bentonite grouting of cracks, (3) unloading of upper slide, and (4) permanent monitoring.	Ramirez Reynaga (1998)/ U.S. Bureau of Reclamation

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
Mexico/Jalisco/ 20.91N, 103.70W	Santa Rosa/ Santiago River	Concrete arch/ Hydroelectric, irrigation(?)	1963/ Government	114/150	400	“Buried” landslide	Both abutments	Old slide in right abutment underlies volcanic mud flow (lahar). Highly jointed rhyolite of left abutment was covered by “large rock falls” (removed?) (Castilla and Colina, 1985). During 1970s, minor progressive rock-wedge movements occurred, triggering additional rock fall. In 1981, rate of movement increased. Remedial measures: (1) rock anchors, (2) drains, and (3) gunniting.	Marsal and Reséndiz (1971), Alberro (1976), Secretaria de Recursos Hidráulicos (1976a, p. 429–473), Castilla and Colina (1985)/ None
Mexico/ Tamaulipas/ 23.96N, 98.66W	Vicente Guerrero/ Soto la Marina River	Rockfill/ Irrigation, water supply, flood control	1971/ Government	63/423	3,900	Talus	Right abutment	Talus on abutment had 6-m maximum thickness. Impervious clay core and sand/gravel transition zones were founded on limestone bedrock abutment after talus was removed from under these zones. Apparently, dam shell (about one half of dam width) was placed on talus and weathered rock. No significant seepage has been noted.	Secretaria de Recursos Hidráulicos (1976b, p. 228–235)/None
Morocco/Fez/ 33.93N, 4.67W	Aït Youb/ Sebou River	Earthfill/ Hydroelectric	1990/ Government	66/Not known	Not known	Ancient landslide dam	Entire foundation and both abutments	Entire valley filled with landslide. Upstream and downstream cofferdams (on landslide) served as buttresses. Other remedial measures: (1) removed part of landslide, (2) added rock buttress, and (3) added downstream drainage.	Bzioui and Chraibi (1991)/None
Morocco/ Tetouan/ 35.44N, 5.40W	Nakhla/ Nakhla River	Rockfill-earthfill/ Water supply	1961/ Government	46/240	5.7	Large landslide in flysch	Left abutment	Large sandstone/shale slide overlying permeable alluvium was overlooked in pre-construction geologic investigation. Remedial measures to reduce seepage: (1) grout curtain, (2) buttresses, (3) impervious diaphragm along dam axis, and (4) drainage gallery. Methods were successful, but extra cost was large.	Barbier (1974), Záruba (1979), Haddaoui and Benabbou (1991)/ None

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
Morocco/Not known/ 34.97N, 3.81W	Saddle Dam F, Mohamed B. A. el Khattabi/ Neckor River	Earthfill/ Irrigation, water supply	1981/ Government	~16/Not known	33.6	Landslide	Foundation	Upon attempted filling of reservoir in 1981, springs occurred downstream. Series of downstream relief wells were installed.	Boufous and Benzekri (1985)/None
New Zealand/ Otago/ 45.19S, 169.35E	Clyde/ Clutha River	Concrete gravity/ Hydroelectric, irrigation	1989/Power company	75/490	320	Dip-slope rock slide in schist	Right abutment	Ancient rock slide in schist (vol. ~60 million m^3) encroaches on right abutment. Lower slope successfully stabilized by buttressing action of dam and by berm placed along right reservoir shore beginning at dam face.	Gillon and Hancox (1991), New Zealand Geomechanics Society (1992), Brown and others (1993), Macfarlane and Gillon (1995), Foster and others (1996, 2000)/None
New Zealand/ East Coast/ 37.34S, 175.79E	Golden Cross tailings dam/ Tributary Waitekauri River	Earthfill-rockfill/ Mine tailings storage	1997/ Gold mining company	40/~400	5	Dip-slope slide in soft volcanics	Entire foundation and both abutments	Tailings dam was constructed on pre-existing 90-million-m^3 slide in weak volcanic rocks. As a result of filling tailings pond and removal of part of toe of landslide, slide was reactivated. Remedial measures considered: (1) drainage and (2) massive toe buttress. Golden Cross mine currently closed because of low value of gold.	Weston and Jacobs (1997)/Consultants' reports
New Zealand/ East Coast/ 37.34S, 175.79E	Union Silt tailings dam/ Tributary Waitekauri River	Earthfill/ Silt control in mine area	1997/Gold mining company	13/~350	0.06	Dip-slope slide in soft volcanics	Entire foundation	Silt-retention dam was constructed on pre-existing 90-million-m^3 slide in weak volcanic rocks (same slide as Golden Cross tailings dam). Remedial measures considered: (1) drainage, (2) massive toe buttress. Golden Cross mine currently closed because of low value of gold.	Weston and Jacobs (1997)/Consultants' reports

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
Papua New Guinea/Eastern Highlands/ 6.25S, 145.98E	Yonki/ Ramu River	Earthfill/ Hydroelectric	1991/ Government	60/680	332	Slump in stiff, fissured clay	Left abutment	During construction in 1987, a significant slide occurred in downstream left abutment of dam. Investigation showed that slide was a reactivation. Design of dam modified to include upstream and downstream berms that act as abutments.	Bosler and others (1991)/Papua New Guinea Electricity Commission
Peru/ Huancavelica/ 12.7S, 74.5W	Tablachaca/ Mantaro River	Concrete gravity/ Hydroelectric	1972/ Government	80/180	16	Slump in phyllite and colluvium	Right abutment	Part of deep-seated slump (‘Derrumbe no. 5”) at right abutment reactivated by reservoir. Active part is only 30–50 m from right end of dam. Movement very slow. From 1982–84, the following costly remedial measures were successfully added: (1) 467,000-m^3 toe buttress, (2) rock anchors, and (3) radial, horizontal, and adit drains. In 2003, abutment area began showing new distress.	Novosad (1979), Novosad and others (1979), Morales Arnao and others (1984), Repetto (1985), Millet and others (1992), de la Torre and others (1997), Garga and de la Torre (2004) /Consultants
Poland/ Bielsko Biala/ 49.65N, 19.21E	Tresna/ Sola River	Earthfill/ Flood control, water supply, hydroelectric, recreation	1967/ Government	37/312	102.7	Rock slide in sandstone and shale	Left abutment	Large sliding wedge (~100,000 m^3) moved along slickensided surface during construction. Most of wedge remains in place. Remedial measures: (1) concrete retaining block and wall, (2) toe buttress, (3) prestressed anchors, and (4) drainage of upper part of slide.	Bujak and others (1967), Hobst and Zajíc (1983, p. 405)/ None
Poland/ Bielsko Biala/ 49.6N 18.8E	Wisla-Czarne/ Vistula River	Earthfill/ Flood control, water supply	1974/Not known	37/271	4.5	Rock slide in shale and sandstone	Right abutment	“At the right side abutment, the huge, presently not active landslide is supported by the body of the dam” (Dluzewski and others, 2000). Inclinometers and piezometers installed in right abutment to monitor possible activity.	Dluzewski and others (2000)/None

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
Slovakia/None/ 48.63N, 17.71E	Čerenec/ Holeska River	Earthfill/ Multipurpose	1964/Not known	10/280	1.7	"Ancient" landslide in clay and sandstone	Right abutment	After construction, seepage occurred through pervious materials in the foundation (not related to landslide). Remedial measures added to dam to increase stability and reduce seepage: (1) earth berm on downstream side of dam and (2) drainage wells.	Lukač (1985)/R. Holzer (Comenius University, oral commun., 1998)
Slovakia/Central Slovakia/ 49.10N, 19.45E	Liptovská Mara/Váh River	Earthfill/ Hydroelectric, flood control, water supply	1976/ Government	53/ 1,250	360	Numerous earth flows and slides	Right abutment	Dam designed so that abutment lies between two slides/flows. Largest, only 150 m upstream from dam axis (but immediately adjacent to edge of dam), stabilized by 700,000-m^3 sand/gravel buttress. Smaller slide separated from downstream edge of dam by fill. Dam system is stable.	Nemcok (1982, p. 298–302), Malgot and others (2002)/ None
South Africa/ Western Cape/ 33.81S, 19.08E	Wemmershoek/ Wemmers River	Rockfill/ Water supply	1957/City government	53/488	58.8	Talus	Both abutments	Layers of talus were encountered along lower slopes of both abutments. During excavation for core trench, talus became unstable due to water, necessitating drainage ditches. Talus removed for core trench.	Brink (1981, p. 215)/ None
Spain/Castellón/ 40.2N, 0.6 W	Arenós/ Mijares River	Rockfill with clay core/ Irrigation	1978/ Government	107/428	137.7	Rock fall and slides	Both abutments	Slides and rock-fall blocks were removed for support of clay core and upstream filters. In 1982 and 1987, large slides occurred near left abutment. Slides were stabilized and anchored. Constant surveillance since.	Andreu and others (1988), Comité Español de Grandes Presas (1993, p. 72–79), Cifres (1998)/ None
Spain/Valencia/ 39.25N, 0.95W	Cortes de Pallás/ Júcar River	Concrete arch-gravity/ Hydroelectric	1989/ Hydroelectric power company	112/312	116	Rock slide in limestone and marl	Left abutment	Large rock slide (vol. ~5 million m^3) barely makes contact with left end of dam. Remediation: 800,000 m^3 excavated from upper part of landslide and moved to lower part to form berm. Apparently successful.	Alonso and others (1993), Lopez Marinas and others (1997)/None

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
Spain/Cordoba/ 37.27N, 4.40W	Iznajar/ Genil River	Concrete gravity/ Irrigation, hydroelectric, water supply	1969/State government	122/407	980	Rock-block slide in limestone	Foundation	"The geology of the dam site….is composed of slided [sic] limestone blocks…." (Bravo, 1967). "Special drainage" measures were installed to insure stability.	Bravo (1967)/None
Spain/Granada/ 36.87N, 3.47W	Rules/ Guadalfeo River	Concrete arch-gravity/ Irrigation, water supply, hydroelectric`	Under construction (1996)/ Federal government	130/610	117	Surficial and deep-seated slides	Mainly left abutment	Surficial slides reactivated by road cuts, etc. Deep-seated slide in phyllite of left abutment is dormant, but could be reactivated. Impervious concrete cutoffs installed in lower parts of both abutments.	Fernández and others (1996), Fernandez del Castillo and others (1997)/J. Chacon (Univ. of Granada, oral commun., 1996)
Spain/Navarra/ 42.61N, 1.17W	Yesa/ Aragón River	Concrete gravity/ Irrigation, hydroelectric, water supply,	1960/ Government	77/398	471	Slide	Right abutment	"Its right abutment leans on a slide zone, what caused very important delays and extra expenses."	García Yagüe and Fernández Montero (1986)/None
Switzerland/ Berne/ 46.4N, 7.3E	Arnensee (d'Arnon)/ Tscherzisbach River	Earthfill/ Hydroelectric	1942–56/ Power company	17/140	10.5	Rock slide	Entire dam	Small dam on tributary of the Sarine River is founded on a natural rock-slide dam. Because of seepage through the foundation, in 1968–69, a 4-m-wide cement-clay grout curtain was injected into foundation to a depth of 5 m.	Comité National Suisse des Grandes Barrages (1976)/ None
Switzerland/ Graubünden/ 46.51N, 9.63E	Marmorera (Castilleto)/ Julia River	Earthfill/ Hydroelectric	1954/Local power company	91/400	62.6	Talus deposit	Left abutment	Left side of dam rests on large pervious talus fan (mainly serpentine detritus, 70 m thick) underlain by alluvium and moraine. Three different treatments: (1) concrete diaphragm into alluvium/moraine, (2) grout curtain (colloidal clay and cement) in talus, and (3) grout curtain in upper bedrock.	Rambert and Gavard (1961), Schnitter (1961), Zingg (1964), Walters (1971, p. 295–296)/None

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
Switzerland/ Glarus/ 46.7N, 9.8E	Rhodannenberg (Klöntal Reservoir)/ Löntsch River	Earthfill/ Hydroelectric	1910/Local government	27/217	56.4	Rock slide	Entire dam	Small dam constructed on natural rock-slide dam to gain additional power head. Considerable seepage through rock-slide foundation. Jet grouting was considered but rejected because of high cost. Monitoring: (1) seepage measuring system and (2) piezometers.	Comité National Suisse des Grandes Barrages (1976, p. 241), International Commission on Large Dams (1983, p. 287), Venzin (1985)/None
Turkey/ 38.52N, 30.71E	Selevir/ Kaliçay River	Earthfill/ Irrigation	Not known/ Federal government	31/470	62.8	Slide in decomposed schist and clay	Right abutment	Slide occurred in right abutment during construction. Outlet tunnel was moved away from abutment and slide. Original outlet tunnel (affected by slide) serves as a drainage outlet. Fill placed at downstream portal as a buttress. Cutoff trench was changed to a concrete cutoff to increase stability.	Sezginer and Karacaoğlu (1961)/ None
United Kingdom/ South Yorkshire/ 53.47N, 1.60W	Broomhead/ Ewden Beck	Earthfill/ Water supply	1934 (repair of 1929 failure)/ County water authority	31/302	5.2	"Slip" in "grits and shales"	Left abutment	Beginning in 1924, hillside slip (caused by reservoir?) damaged valve tower and within a few years threatened overflow weir. Remedial measures: (1) surface-drain trench filled with free-draining rubble, and (2) removal of ~300,000 m^3 of material from the slide mass. In 1930, 6 million kg of cement was injected to reduce leakage.	Bromehead (1936), Walters (1971, p. 63–67), International Commission. on Large Dams (1974, p. 530), Legget and Karrow (1983, p. 25–51 to 25–52)/ None
United Kingdom/ Shropshire/ 52.64N, 2.53W	Devil's Dingle/ Tributary Severn River	Earthfill/ Fly-ash disposal	Continuing construction/ Electric power company	64/570	1.68	"Landslipping" in mudstone	Foundation	Information obtained from foundation boreholes showed wider extent of pre-existing slip surfaces than previously thought. Thus, design of downstream slope was flattened to increase stability. Shallow slips in valley sides stabilized by trench drains.	Haws and others (1985)/None

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United Kingdom/ Leicester/ 52.66N, 0.59W	Empingham/ Gwash River	Earthfill/ Water supply	1975/ Government water-supply authority	40/ 1,200	4.7	Cambering and valley bulging	Foundation	Construction showed pre-existing cambering and valley bulging in the “boulder-clay” (i.e., glacial till) foundation. Cruden and Varnes (1996) infer that a camber in periglacial soils may be described as a “relict, complex soil spread–soil topple.” No negative effects on dam foundation.	Chandler (1976), Horswill and Horton (1976), Hutchinson (1988), Cruden and Varnes (1996)/None
United Kingdom/ Cheshire/ 53.2N, 2.1W	Trentabank/ Bollin River	Earthfill/ Water supply	1929/Local water-supply authority	23/245	0.59	Slide in sandstone and shale	Both abutments and foundation	Before construction, “grits” (soft sandstone) and shales had slid toward the valley. Slopes of dam were designed to be very flat to prevent further disturbance.	Walters (1971, p. 93–95)/None
United Kingdom/ Derbyshire/ 53.50N, 1.84W	Woodhead No.1/ Etherow River	Apparently earthfill/Water supply	Failed 1850/ Local water-supply authority	Not known/ Not known	Not known	“Land-slips”	Abutment in “steep-sided valley”	“A dam was actually completed in landslipped material, but the leakage was so serious that it was abandoned ***”(Bromehead, 1936).	Lapworth (1911), Bromehead (1936)/ None
United Kingdom/ Derbyshire/ 53.50N, 1.84W	Woodhead No. 2/ Etherow River	Earthfill/ Water supply	1877/Local water-supply authority	29/140	5.4	“Land-slips”	Abutment	Ancient slides in shale and sandstone exposed in trench for concrete cutoff. “***a fresh site close at hand [close to site of Woodhead No.1] was chosen,***, a good bottom in impervious shale was found. One end was again in a landslip; ***” (Bromehead, 1936). Problem partly overcome by taking new heading into hillside.	Lapworth (1911), Bromehead (1936), Richey (1959, p. 67, 69)/None
United States/ Alaska/ 55.43N, 131.67W	Lake Connell/ Ward Creek	Concrete gravity/ Water supply for pulp mill	1953/Private company	29/183	13.6	Rock slide in phyllite leaving overhang	Left abutment	During construction, a rock slide occurred on steep slope of left abutment, leaving an unstable overhang. To remove overhang would have caused a setback in construction schedule. Thus, overhang was underpinned with prestressed steel shoring, and volume of rock lost in slide was replaced with concrete, which became part of dam.	Shannon and Shannon (1954)/ None

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Arizona/ 35.09N, 108.79W	Black Rock (Zuni)/Zuni River tributary	Earthfill-rockfill/ Irrigation, recreation	1908/ Federal government	36/238	3.22	Rock fall (collapse of basalt abutment), talus	Both abutments	Left abutment: continuing fall of basalt blocks due to piping of underlying alluvium. Right abutment: talus cover. Considerable seepage through both abutments. Remedial measures being considered: (1) covering basalt with impervious material, (2) grouting the basalt beds, (3) horizontal impervious blanket, and (4) vertical cutoff trench.	Taylor and others (2001), Kocahan and Taylor (2002)/U.S. Bureau of Reclamation
United States/ California/ 37.13N, 121.93W	Austrian/ Los Gatos Creek	Earthfill/ Water supply	1950/Water-supply public utility	56/213	9.4	Slides in sandstone and siltstone	Right and possibly upper-left abutments	Right abutment consists of debris from large Quaternary slide. M7.1 Loma Prieta quake (1989) reactivated part of slide causing major damage to spillway, which was rebuilt at left end of dam. Spillway relocation required removal of large quantity of rocky landslide material from left abutment. Grouting in 1993 in both abutments.	McLaughlin and others (1991), Pardini and Reichert (1993)/Consultants' reports; California Division of Safety of Dams
United States/ California/ 37.06N, 121.08W	B.F. Sisk (San Luis)/ San Luis Creek	Earthfill/ Irrigation, hydroelectric, recreation	1967/Federal and State governments	116/ 5,669	2,540	Slide in clay slopewash and dam materials	Left abutment	During drawdown in 1981, slide occurred in "hard" clay slopewash of left abutment and passed through the upstream face of the dam. Slide moved about 20 m. Reservoir was not threatened. Remedial measures: (1) construction of a "keyed" berm at upstream toe of dam and (2) reconstruction of face of dam.	Von Thun (1985), Subcommitee on Dam Incidents and Accidents (1988, p. 164–165)/None
United States/ California/ 34.29N, 118.18W	Big Tujunga No.1/Big Tujunga Creek	Concrete arch/ Water supply, flood control	1931/County government	63/154	87	Massive granite block slide	Right abutment	Controversy as to whether or not toe of large rock-block slide upslope from right abutment is at the contact with end of the dam. Morton and Streitz (1969) think it is; county geologists say it isn't. Discussion is academic in that right abutment seems completely stable because of large size of slide mass. Has been absolutely no movement.	Morton and Streitz (1969)/Los Angeles County reports, D. M. Morton (oral commun., 1997)

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ California/ 39.45N, 123.39W	Brooktrails No. 3 North/ Willits Creek	Earthfill/ Water supply, recreation, irrigation, flood control	1970/Private	14/117	0.6	Earth slide	Left abutment	There are several slides in vicinity of the dam. In 1971, slide activity (reactivation?) damaged retaining wall at spillway. Slope was rebuilt. Remedial measures: (1) slope reshaped and (2) network of deep intersecting drains added.	Committee on Failures and Accidents to Large Dams (1976, p. 127–128)/ California Division of Safety of Dams; consultant's reports.
United States/ California/ 37.49N, 121.82W	Calaveras/ Calaveras Creek	Earthfill/ Water supply	1925/City government	75/366	163	Major slide in shale and sandstone	Right abutment	Disagreement as to existence of large slide at right abutment. Nilsen (1972) mapped large slide. Kintzer (1980) stated slide was small and was removed during construction. Field reconnaissance by author from distance noted large slide still exists; however, slide is so large that it poses no stability problem.	Cotton (1972), Nilsen (1972b), Kintzer (1980)/California Division of Safety of Dams; consultant's reports; W. Cotton (oral commun., 1997)
United States/ California/ 34.37N, 119.33W	Casitas/ Coyote Creek	Earthfill/ Irrigation, water supply, recreation	1959/ Federal government	102/607	354	Slide in sedimentary rocks	Lower right abutment	Landslide in shale, siltstone, and sandstone largely avoided by modifying axis alignment. In final design, only a small amount of landslide toe underlies downstream edge of embankment. No problems.	Dibblee (1988)/U.S. Bureau of Reclamation reports
United States/ California/ 34.52N, 118.60W	Castaic/ Castaic Creek	Earthfill/ Water supply, recreation, irrigation, hydroelectric	1973/State government	125/ 1,585	450	Block glides in shale	Mainly in left abutment	Old slides, as much as 35 m thick, led to shifting design of dam axis to minimize effects. However, considerable slide activity occurred during construction. Remedial measures: (1) partial removal of slide material, (2) resloping of cuts, (3) large toe buttresses, and (4) grouting. Studies of unstable areas in left abutment conducted as late as 1995.	Hanegan (1973), Glover and others (1997)/ California Division of Safety of Dams

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ California/ 37.40N, 121.76W	Cherry Flat/ Penitencia Creek	Earthfill/ Water supply	1936/City government	18/70	0.86	Slides in sedimentary rocks	Both abutments	Both abutments are in "blue clay," formed of sheared and decomposed Franciscan Fm. shale and sandstone. Remedial measure: left abutment cutoff trench was extended to firm material. Apparently, there are no stability problems.	None/California Division of Safety of Dams
United States/ California/ 37.12N, 121.55W	Coyote/ Coyote Creek	Earthfill-rockfill/ Irrigation	1936/County water-supply district	43/299	30.2	Shale slide	Spillway area at right abutment	"Slide No. 2 appears to be, in part, a reactivated portion of an ancient landslide, most of which was excavated during construction of the spillway." Reactivation of this slide damaged spillway. Drainage system was recommended to reduce slide potential.	None/Santa Clara Water District report; field visit
United States/ California/ 37.81N, 122.00W	Danville/ Offstream	Earthfill/Water supply	1961/Public utility district	23/233	0.06	Massive landslide complex in sedimentary rocks	Entire dam and reservoir	City water-supply dam and reservoir built on Quaternary landslide complex (dimensions: ~5 km x 1 km). Thickness of slide under reservoir is ~30 m. No evidence of slide movement in thousands of years, nor of lack of stability of dam.	Nilsen (1973), Dibblee (1980)/ Consultants' reports
United States/ California/ 36.40N, 120.84W	Hernandez/ San Benito River	Earthfill/ Recreation, irrigation	1962/County government	38/290	39.2	Slide in shale and serpentinite	Left abutment	Most landslide detritus (mainly serpentinite) was removed from under left abutment core trench. Dental work where necessary. Left abutment shells were founded on landslide materials, but loose material was removed. As of 1981 inspection, minor slides adjacent to left abutment were active, but dam was stable.	None/Consultants' reports; California Division of Safety of Dams

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ California/ 37.32N, 119.32W	Mammoth Pool/ San Joaquin River	Earthfill/ Hydroelectric	1959/ Private electric power company	125/250	152	Mainly rock fall	Entire foundation	Original valley bottom blocked by rock-fall deposits from sheeted granodiorite that impounded a lake 2.5 km long. Boulders as large as 5,000 m^3. Remaining sheets were removed or bolted to canyon walls. Cutoff trench constructed 30 m through detritus to bedrock. Blocks at cutoff trench in valley bottom were broken up or removed, but were left in place under upstream outer shell. Pervious drain and filter zone prevent migration of fine material from embankment into voids in foundation.	Terzaghi (1962), Hamilton (1992), Goodman (1993, p. 242–243)/ Consultants' and company reports
United States/ California/ 37.52N, 121.91W	Mayhew Reservoir/ Offstream (downstream from Fremont)	Earthfill/ Water supply	1962/ Public utility district	16/255	0.022	Flow part of slump-flow	Entire foundation and reservoir	This rectangular dam/reservoir lies on toe of the Reservoir landslide, part of the Mission landslide complex. Reservoir landslide is thought to be dormant. However, in 1994 reservoir-lining distress resulting from active landslide movement was observed on the eastern (upslope) part of the dam. Recommended remedial measure: gravel-filled drainage trenches.	None/California Division of Safety of Dams; consultants' reports
United States/ California/ 34.34N, 117.23W	Mojave/West Fork Mojave River	Earthfill/ Flood control	1971/ Federal government	64/670	194	Earth slide	Left abutment	Small slide occurred in left abutment during construction. Remedial measures: (1) two berms to buttress abutment and (2) redesign left end of dam.	Subcommittee on Dam Incidents and Accidents (1988, p. 132)/ None
United States/ California/ 37.05N, 121.29W	North Fork (Pacheco Lake)/ Pacheco Creek	Earth fill/ Water supply, irrigation	1939/Public utility district	30/323	11.1	Slide in sandstone, siltstone, and shale	Left abutment	Entire left abutment area exhibited landslide topography. Spillway excavation led to reactivation late in 1938. Area was drained and buttressed. Movement again in 1966–67. Spillway repaired in 1967; still showed damage in 1997. Left abutment and spillway wall continue to be unstable.	Nilsen (1972a)/ California Division of Safety of Dams; consultants' reports

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ California/ 34.34N, 118.40W	Pacoima/ Pacoima Creek	Concrete arch/ Flood control	1929/County government	111/195	11.4	Rock-block slide in banded gneiss	Left abutment	Large rock block, serving as thrust block for left end of dam, recognized as possible problem during design and construction of dam. Stabilized by anchors. Northridge earthquake (1994) caused slump of 200 mm and horizontal displacement of 250 mm. New remedial measures: (1) post-tensioned tendon anchor system, (2) foundation/abutment grouting, and (3) gunniting.	Sharma and others (1997)/ California Division of Safety of Dams, Los Angeles County safety reports; consultants' reports
United States/ California/ 34.55N, 118.51W	St. Francis/ San Francisquito Creek	Concrete gravity-arch/ Water supply, irrigation	1926/City government	62/~400	47	Huge pre-existing slides in schist	Left abutment	As reservoir approached capacity during first filling (1928), dam failed causing catastrophic flood that drowned about 450 people. Cause of failure originally thought to be fault in right abutment. However, later research indicated failure occurred as reactivation of series of Pleistocene slides in schist of left abutment.	Willis (1928), Outland (1977), Rogers (1992, 1995, 1997)/None
United States/ California/ 34.16N, 117.78W	San Dimas/ San Dimas Creek	Concrete gravity-arch/ Flood control, irrigation	1922/County government	40/104	2.28	Pre-existing rock slides	Both abutments	Slides in heavily jointed gneisses of both abutments were recognized before construction. Remedial measures: (1) dam shape modified, (2) foundation grouted, (3) 4,500 m^3 of rock removed from upper right-abutment slopes, and (4) steel tendons and post-tensioned anchors installed. Now stable.	None/California Division of Safety of Dams; Los Angeles County Flood Control District
United States/ California/ 40.82N, 123.96W	Sweasey/ Mad River	Composite concrete arch and earthfill/ Water supply	1936/City government	23/61	1.5	Slide in sandstones and shales	Left abutment	During construction, slide occurred in left abutment Franciscan Group sandstones and hard, clayey shales. Dam was redesigned from a full masonry arch to a composite section employing an arch dam across the channel section, which abutted a massive concrete thrust block at the left end. An earthfill section then connected the thrust block with the excavated left abutment. Design height was also reduced about 20 m. Dam was later breached because of siltation in the reservoir.	Kiersch and James (1991)/City of Eureka

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province /latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ California/ 35.17N, 120.53W	Terminal/ Tributary Arroyo Grande Creek	Earthfill/ Water supply	1969/County public utility	16/168	1.34	Bedding-plane slide in shale	Left abutment	Preconstruction field studies found "old buried landslide" in soft shale. Much of the slide was excavated during construction. Additional stability provided by addition of 6.5-m-high upstream and downstream berms.	Cavallin (1991)/ California Division of Safety of Dams
United States/ California/ 40.80N, 122.76W	Trinity/ Trinity River	Earthfill/ Irrigation	1962/Federal government	164/792	3,400	Slides in sedimentary rocks and metavolcanics	Both abutments	Slide at upstream right abutment removed during construction. Large slide at downstream right abutment was partially removed; closely monitored remainder is adjacent to corner of dam, endangering spillway stilling basin. Toe of third potential slump is buttressed by left end of dam, and poses no threat.	Walker and Harber (1961), Bock and Harber (1974)/ U.S. Bureau of Reclamation
United States/ California/ 34.98N, 120.32W	Twitchell/ Cuyama River	Earthfill/ Irrigation, flood control	1958/Federal government	73/550	491	Slide in shale and siltstone	Left abutment	Downstream left margin of dam shell is barely in contact with large landslide. No problems. Large ancient slides present on reservoir shore.	Hall (1978)/None
United States/ Colorado/ 39.10N, 107.88W	Atkinson/ Atkinson Creek	Earthfill/ Irrigation, hydroelectric	1893/Federal government	11/229	2.5	Massive rock glide	Entire dam and reservoir	Entire dam and reservoir are on Grand Mesa landslide complex (mainly basalt on claystone, mantled by glacial deposits). Seepage from both abutments has been a continuing problem.	Yeend (1969, 1973), Colton and others (1975c), Baum and Odum (1996, 2003)/U.S. Bureau of Reclamation; Colorado Division of Water Resources
United States/ Colorado/ 38.82N, 107.45W	Beaver/ Minnesota Creek tributary	Earthfill/ Irrigation, fire protection, recreation	1958/Private	34/296	2.3	Shear and collapse of sedimentary rocks	Both abutments	Abutments and foundation are composed of sandstone, shale, and coal. Coal has burned naturally, reducing support for remaining layers, which have failed locally. Abutment leakage led to 1997 installation of 60-mil impervious liner at both ends of dam.	None/Consultants' reports; Colorado Division of Water Resources

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Colorado/ 37.60N, 106.67W	Beaver Park/ Beaver Creek	Earthfill/ Recreation, fish, irrigation	1912/State government	35/133	7.2	Apparent rock slide	Right abutment	Abutment composed of badly fractured latite tuff mapped as "landslide" by Hunter (1918), has been stable, but has leaked considerably through the years.	Hunter (1918)/ Colorado Division of Water Resources
United States/ Colorado/ 39.08N, 108.03W	Big Beaver/ Bull Creek tributary	Earthfill/ Irrigation	1936/Private	11/55	0.25	Massive rock slide	Entire dam and reservoir	Entire dam and reservoir on Grand Mesa landslide complex (mainly basalt on claystone, mantled by glacial deposits). Seepage through foundation in 1992. Continuing seepage both north and south of the dam.	Yeend (1969, 1973), Colton and others (1975e), Baum and Odum (1996, 2003)/ Colorado Division of Water Resources
United States/ Colorado/ 39.54N, 106.22W	Black Lake No.1/Black Gore Creek	Earthfill/ Water supply, recreation	1939 (rebuilt 1995)/Local government	~18 (after raising)/122	0.4(?) (conflicting data)	Debris flow from ancient landslide	Right abutment	Original dam raised to ~18 m (including cutoff) in 1995. Much of original landslide removed. Cutoff trench to sound bedrock. Grout curtain was placed to competent bedrock in foundation and right abutment.	None/Colorado Division of Water Resources; consultant's report
United States/ Colorado/ 39.10N, 107.90W	Bonham/Big Creek	Earthfill/ Irrigation, hydroelectric	1900/Federal government	12/457	2.8	Massive rock slide	Entire dam and reservoir	Entire dam and reservoir on Grand Mesa landslide complex (mainly basalt on claystone, mantled by glacial deposits). Minor foundation seepage.	Yeend (1969, 1973), Colton and others (1975c), Tweto and others (1978), Baum and Odum (1996, 2003)/U.S. Bureau of Reclamation
United States/ Colorado/ 40.13N, 107.02W	Burnt Mesa/ S. branch of Hunt Creek tributary	Earthfill/ Irrigation	1957/Private	12/83	0.3	Slide in shale	Right abutment	Right abutment is in shale slide. In 1987, seepage occurred in right abutment area. However, landslide generally has had no negative effect on dam.	Colton (1975f), Madole (1989)/ Colorado Division of Water Resources; R. Madole (U.S. Geological Survey, oral commun., 2002)

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Colorado/ 39.05N, 107.85W	Cedar Mesa/ Surface Creek	Earthfill/ Irrigation	1944/Private	14/381	1.7	Massive rock slide	Entire dam and reservoir	Entire dam and reservoir on Grand Mesa landslide complex (mainly basalt on claystone, mantled by glacial deposits). "Blowout" (1971) in foundation at left abutment corrected by vinyl membrane; satisfactory performance since.	Yeend (1969, 1973), Colton and others (1975c)/Colorado Division of Water Resources; consultant's report
United States/ Colorado/ 39.67N, 105.70W	Clear Lake/ South Clear Creek	Rockfill/ Hydro-electric, recreation	1914/Public utility	12/55	0.6	Rock slide	Entire dam foundation and both abutments	Dam was built on landslide dam formed by rock slides and talus from both valley walls. Seepage and piping occurred through left-abutment talus, resulting in "sinkholes" (1997). Remedial grouting in talus.	Widmann and Miersemann (2001); Hammer (2002)/ Colorado Division of Water Resources; R. Madole (U.S. Geological Survey, oral commun., 2002)
United States/ Colorado/ 39.27N, 107.72W	Currier #2/ Buzzard Creek	Earthfill/ Irrigation, fire protection, stock	1968/Private	13/112	0.5	Slide in shale and sandstone	Left abutment	Left abutment is in "young landslide," which is in "state of metastable equilibrium" (Soule, 1988). In 1993–94, slide on left abutment encroached on emergency spillway; problem solved by diverting water from distressed area. No other problems.	Soule (1988)/ Colorado Division of Water Resources; U.S. Natural Resources Conservation Service
United States/ Colorado/ 40.17N, 107.67W	D.D.&E. Wise (Aldrich Lake)/Hulch Creek diversion ditch	Earthfill/ Irrigation	1946/Private	12/104	1.8	Massive slide in shale	Entire dam and reservoir	D.D.&E. Wise Dam and its reservoir, Aldrich Lake, are located on the eastern edge of a massive 13-km^2 landslide in Mancos Shale. Landslide material has had no negative effect on dam or reservoir performance.	Colton and others (1975f), Reheis (1984), Madole 1989)/Colorado Division of Water Resources; R. Madole (U.S. Geol. Survey, oral commun., 2002)

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Colorado/ 39.04N, 107.95W	Eggleston/ Kiser Creek	Earthfill/ Irrigation	1949/Private	12/101	5.0	Massive rock slide	Entire dam and reservoir	Entire dam and reservoir are on Grand Mesa landslide complex (mainly basalt on claystone, mantled by glacial deposits). Very minor seepage; no serious problems.	Yeend (1969, 1973), Colton and others (1975c), Baum and Odum (1996, 2003)/ Colorado Division of Water Resources
United States/ Colorado/ 38.83N, 107.96W	Fruitgrowers/ Alfalfa Run Creek	Earthfill/ Irrigation, recreation	1939/Federal government	17/463	9.3	Apparent slide in shale	Left abutment	Slow movement along gently dipping failure surface began in late 1990s. At present, Bureau of Reclamation is trying to define and solve the problem.	None/U.S. Bureau of Reclamation
United States/ Colorado/ 39.04N, 107.68W	Goodenough #2/Leroux Creek tributary	Earthfill/ Irrigation, water supply	1928/Private	12/232	1.5	Massive rock slide	Entire dam and reservoir	Entire dam and reservoir are on Grand Mesa landslide complex (mainly basalt on claystone, mantled by glacial deposits). Minimal foundation leakage at toe.	Yeend (1969, 1973), Colton and others (1975c), Baum and Odum (1996, 2003)/ Colorado Division of Water Resources
United States/ Colorado/ 39.00N, 108.04W	Granby #12/ Dirty George Creek tributary	Earthfill/ Irrigation	1949/Private	10/273	1.3	Massive rock slide	Entire dam and reservoir	Entire dam and reservoir are on Grand Mesa landslide complex (mainly basalt on claystone, mantled by glacial deposits). Foundation seepage during 1970s caused small slumps in toe of embankment. Minor foundation seepage still occurs.	Yeend (1969, 1973), Colton and others (1975e), Ellis and Gabaldo (1989), Baum and Odum (1996, 2003)/Colorado Division of Water Resources
United States/ Colorado/ 39.95N, 105.36W	Gross/South Boulder Creek	Concrete gravity/ Water supply, hydroelectric, recreation	1955/Public utility	104/332	58.7	Deep-seated rock slide	Both abutments	Wahlstrom (1974, p. 74) noted deep-seated “gravity-slip surfaces in steep-walled canyon in massive crystalline rock.” No effect on dam performance. Dam forms buttress against any future movement.	Wahlstrom (1974, p. 74, 77-79)/None

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Colorado/ 40.84N, 106.99W	Hahn's Peak/ Willow Creek	Earthfill/ Recreation, fish and wildlife	1978/State government	12/82	1.0	Slide in shale	Left abutment	Slide in shale of Morrison Formation serves as left abutment. No problems have developed.	Madole (1991b)/ Colorado Division of Water Resources; R. Madole (U.S. Geol. Survey, oral commun., 2002)
United States/ Colorado/ 39.00N, 108.11W	Hogchute/ Kannah Creek	Earthfill/Water supply	1947/City government	17/189	1.1	Rock slide	Entire dam and reservoir on landslide	Entire dam and reservoir on part of Grand Mesa landslide complex (mainly basalt on claystone, mantled by glacial deposits). Right abutment is on basalt talus. No negative effects on dam.	Yeend (1969, 1973), Colton and others (1975d), Ellis and Gabaldo (1989)/ Colorado Division of Water Resources
United States/ Colorado/ 40.12N, 107.02W	Joe Wright/ Joe Wright Creek	Earthfill/ Water supply, irrigation, recreation	1979/City government	45/701	11.5	Huge rock slide	Right abutment and right end of dam	Entire right valley wall is huge Quaternary landslide mass (volcanics over sedimentary rocks), probably formed upon glacier retreat. No problems.	Colton and others (1975b)/None
United States/ Colorado/ 40.06N, 106.45W	Jones #2/ Sheep Creek tributary	Earthfill/ Water supply, irrigation	1887/Private	12/99	0.7	Massive block glide	Entire dam and reservoir	Entire dam and reservoir lie on 13-km^2 glide block in Niobrara and Dakota Formations shales and sandstones. Abutments are in fractured shales, resulting in seepage from toe drains. Reservoir serves as water supply for City of Kremmling.	Barclay (1968, p. 157), Izett and Barclay (1973), Colton and others (1975f), Madole (1991a)/ Colorado Division of Water Resources; R. Madole (U.S. Geological Survey, oral commun., 2002)

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Colorado/ 39.06N, 107.84W	Kehmeier/ Surface Creek tributary	Earthfill/ Irrigation	1949/Private	10/172	0.5	Massive rock slide	Entire dam and reservoir	Entire dam and reservoir on Grand Mesa landslide complex (mainly basalt on claystone, mantled by glacial deposits). Minor seepage through both abutments.	Yeend (1969, 1973), Colton and others (1975c), Tweto and others (1978)/ Colorado Division of Water Resources
United States/ Colorado/ 39.03N, 107.96W	Kennicott Slough/Kiser Creek tributary	Earthfill/ Irrigation	1946/Private	12/380	1.5	Massive rock slide	Entire dam and reservoir	Entire dam and reservoir on Grand Mesa landslide complex (mainly basalt on claystone, mantled by glacial deposits). Minor seepage through left abutment; performance generally good.	Yeend (1969, 1973); Colton and others (1975c), Tweto and others (1978), Baum and Odum (1996, 2003)/Colorado Division of Water Resources
United States/ Colorado/ 39.02N, 107.95W	Kiser Slough/ Kiser Creek	Earthfill/ Irrigation, recreation	1950/Private	12/320	0.9	Massive rock slide	Entire dam and reservoir	Entire dam and reservoir on Grand Mesa landslide complex (mainly basalt on claystone, mantled by glacial deposits). Foundation leakage; drainage trenches added as remedial measure have improved situation.	Yeend (1969, 1973), Colton and others (1975c), Tweto and others (1978), Baum and Odum (1996, 2003)/Colorado Division of Water Resources
United States/ Colorado/ 39.04N, 107.88W	Knox/ Surface Creek tributary	Earthfill/ Irrigation	1954/Private	12/156	0.5	Massive rock slide	Entire dam and reservoir	Entire dam and reservoir on Grand Mesa landslide complex (mainly basalt on claystone, mantled by glacial deposits). Minor seepage from both abutments.	Yeend (1969, 1973), Colton and others (1975c), Tweto and others (1978), Baum and Odum (1996, 2003)/Colorado Division of Water Resources

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Colorado/ 40.97N, 107.33W	Lower Cogdill/ Government Corral Creek	Earthfill/ Water supply, fish and wildlife, fire protection	1956/Private	12/146	0.4	Massive slide in shale and sandstone	Entire dam and reservoir	Entire dam and reservoir lie in large (18 km^2) landslide area overlying Lewis Shale and Mesaverde Group (sandstone and shale). Landslide deposits have had no negative effect on dam/reservoir performance.	Colton and others (1975f), Madole (1982)/Colorado Division of Water Resources; R. Madole (U.S. Geological Survey, oral commun., 2002)
United States/ Colorado/ 40.30N, 106.29W	Matheson/ Troublesome Creek	Earthfill/ Irrigation	1951/Private	18/59	2.2	Massive slide in Tertiary volcanics	Left abutment and possibly foundation	Dam was built on NE edge of large landslide area in Tertiary volcanics overlying Morrison Fm. sandstones and shales. Seepage in right abutment area through "shattered lava." Clay blanket installed to prevent seepage, apparently with little success.	Madole (1991a)/ Colorado Division of Water Resources; R. Madole (U.S. Geological Survey, oral commun., 2002)
United States/ Colorado/ 40.14N, 106.47W	McElroy/ Pass Creek	Earthfill/ Irrigation	1931/Private	15/76	0.5	Earth flow	Right abutment	Earth flow from Dakota Fm. shales originally dammed Pass Creek. Serves as right abutment and part of foundation. Generally very little seepage; minor seepage at right groin in 1975.	Izett and Barclay (1973), Colton and others (1975f), Madole (1991a)/ Colorado Division of Water Resources; R. Madole (U.S. Geological Survey, oral commun., 2002)
United States/ Colorado/ 39.21N, 107.75W	McKelvie #1/ Plateau Creek tributary	Earthfill/ Irrigation	1943/Private	11/137	0.5	"Old landslide"	Entire dam	Entire dam is in area mapped by Soule (1988) as "old landslide." Minimal foundation seepage (slightly boggy downstream; no flowing water). Dam performance good.	Soule (1988)/ Colorado Division of Water Resources

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Colorado/ 39.04N, 107.93W	McKoon/ Young's Creek	Earthfill/ Irrigation	1948/Private	10/84	0.3	Massive rock slide	Entire dam and reservoir	Entire dam and reservoir are on Grand Mesa landslide complex (mainly basalt on claystone, mantled by glacial deposits). No negative effects on dam.	Yeend (1969, 1973), Colton and others (1975c), Tweto and others (1978), Baum and Odum (1996, 2003)/Colorado Division of Water Resources
United States/ Colorado/ 40.18N, 106.57W	McMahon #2/ Red Dirt Creek	Earthfill/ Irrigation	1945/Private	15/301	6.5	Slump-earth flow	Left abutment	Left abutment is slump–earth flow in Morrison Fm. shale and sandstone. Landslide apparently has had no negative effect on dam performance.	Madole (1991a)/ Colorado Division of Water Resources; R. Madole (U.S. Geological Survey, oral commun., 2002)
United States/ Colorado/ 40.27N, 106.56W	Milk Creek/ Milk Creek	Earthfill/ Irrigation	1925/Private	11/43	0.2	Massive slide in shale and sandstone	Entire dam and reservoir	Entire dam and reservoir lie in large landslide area in Benton Shale and Dakota Sandstone. Landslide material has had no negative effects on dam performance.	Colton and others (1975f), Madole (1991a)/Colorado Division of Water Resources; R. Madole (U.S. Geoogical Survey, oral commun., 2002)
United States/ Colorado/ 38.88N, 107.47W	Monument/ Minnesota Creek tributary	Earthfill/ Irrigation	1889/Private	23/129	0.8	Rock slide	Left abutment	Slide mass, which extends vertically 120 m above left end of dam and 450 m laterally, consists mainly of sandstone cobbles and boulders in clay matrix. Instrumented since 1992 to record dam movement; however, there has been no distress. Apparently no significant remedial measures have yet been needed.	Colton and others (1975g), Norfleet and Marvin (1995)/ Colorado Division of Water Resources

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Colorado/ 39.11N, 107.75W	Monument #1/Monument Creek	Earthfill/ Irrigation	1960/Private	11/152	1.1	Massive rock slide	Entire dam and reservoir	Entire dam and reservoir on Grand Mesa landslide complex (mainly basalt on claystone, mantled by glacial deposits). Some seepage from left abutment.	Yeend (1969, 1973), Colton and others (1975c)/Colorado Division of Water Resources
United States/ Colorado/ 37.39N, 105.39W	Mountain Home/ Trinchera Creek	Earthfill/ Irrigation, fisheries	1906/Private	47/145	32.0	Rock-block slide	Left abutment	Slide in basalt underlain by siltstone and sandstone. No movement since construction. Because overflow spillway crosses slide block, possible instability was conjectured. However, 1993 analysis indicated no stability problem.	None/Colorado Division of Water Resources; consultants' reports
United States/ Colorado/ 40.55N, 106.02W	North Michigan Creek/ Michigan River	Earthfill/ Recreation, fish and wildlife	1963/State government	23/142	3.6	Earth flow	Left (and possibly right) abutment	Left abutment (and possibly right abutment) is on landslide masked by glacial deposits. Except for minor right-abutment seepage, landslide has had no negative effect on dam.	Madole (1991b)/ Colorado Division of Water Resources; R. Madole (U.S. Geological Survey, oral commun., 2002)
United States/ Colorado/ 39.08N, 107.65W	Overland #1/ Cow Creek (Muddy Creek tributary)	Earthfill/ Irrigation	Originally in early 1900s; rebuilt 1987/ Private	26/975	10.1	Rock slide	Entire dam	Entire dam and reservoir on huge rock slide. Before 1987, toe-buttress stability problems possibly due to landslide material. In 1987, toe-buttress drains installed and material added to toe buttress.	Yeend (1969, 1973), Colton and others (1975c)/Colorado Division of Water Resources
United States/ Colorado/ 39.05N, 107.88W	Park/Surface Creek	Earthfill/ Irrigation	1940/Private	14/229	5.6	Massive rock slide	Entire dam and reservoir	Entire dam and reservoir are on Grand Mesa landslide complex (mainly basalt on claystone, mantled by glacial deposits). Slide material is fragmental basalt and fairly permeable. Thus, there have been seepage problems (~75–115 l/min) through base of left abutment). Bentonite added to abutment in 1997 to slow seepage.	Yeend (1969, 1973), Colton and others (1975c), Tweto and others (1978), Baum and Odum (1996, 2003)/Colorado Division of Water Resources

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Colorado/ 40.27N, 106.41W	Parsons/ Carter Creek	Earthfill/ Irrigation, stock	1952/Private	12/84	0.2	Slide in Pierre Shale	Left abutment and spillway	Left abutment and original spillway in toe of pre-existing Pierre Shale slide. There was difficulty with the spillway; so it was moved from the slide. Some seepage still flows from slide.	Colton and others (1975f), Madole (1991a)/Colorado Division of Water Resources; consultants' reports; R. Madole (U.S. Geological Survey, oral commun., 2002)
United States/ Colorado/ 37.35N, 106.54W	Platoro/ Conejos River	Rockfill-earthfill/ Irrigation	1951/Federal government	50/270	83.6	Massive slump block	Left abutment	Left abutment is toe of large (length >1 km) andesite slump block. Abutment is stable. No seepage problems.	None/U.S. Bureau of Reclamation; Colorado Division of Water Resources
United States/ Colorado/ 40.13N, 107.26W	Poose Creek/ Poose Creek	Earthfill/ Recreation, fish and wildlife	1969/State government	12/133	0.67	Slide in volcanics, shale, glacial deposits	Right abutment (possibly entire dam)	Dam was built on mixture of landslide/glacial deposits left behind as glacier retreated from valley. Slide is a mixture of shale/sandstone (Browns Park, Morrison, and Dakota Fms.), of overlying Tertiary volcanics, and glacial deposits. No negative effects on dam.	Colton and others (1975f), Madole (1989)/Colorado Division of Water Resources; R. Madole (U.S. Geological Survey, oral commun., 2002)
United States/ Colorado/ 38.15N, 107.75W	Ridgway/ Uncompahgre River	Earthfill/ Irrigation, water supply, recreation, flood control	1987/Federal government	101/740	101	Slides in siltstone, sandstone, and mudstone	Left abutment	Relatively small slide masses uncovered during construction; minor sliding occurred. Most slide debris then removed. Remainder buttressed by dam embankment; thus, the abutment is stronger than originally.	Von Thun (1987)/ U.S. Bureau of Reclamation

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Colorado/ 37.72N, 107.27W	Rio Grande/ Rio Grande River	Earthfill/ Irrigation	1916/Private	35/329	64.4	Rock slide	Left abutment	Huge andesite slide at and above left abutment (Atwood, 1918). Considerable seepage led to reconstruction of abutment featuring: (1) retaining wall, (2) french drains, and (3) horizontal drains. Installation of piezometers and inclinometers.	Atwood (1918, p. 18–20), Atwood and Mather (1932, p. 157)/Colorado Division of Water Resources; consultants' reports
United States/ Colorado/ 40.14N, 106.20W	Scholl/Corral Creek	Earthfill/ Irrigation	1964/Private	18/55	0.8	Rock slide	Right abutment	Right end of dam abuts against slide of basalt boulders up to 2 m in diameter derived from basalt flows in upper valley wall. Serious seepage through this pervious mass. In 1964, right groin was grouted. In 1965, 1972, 1989–90, impermeable membranes were placed in right abutment, but seepage continued; sinkholes formed on surface.	Colton and others (1975f), Madole (1991a)/Colorado Division of Water Resources; R. Madole (U.S. Geological Survey, oral commun., 2002)
United States/ Colorado/ 40.15N, 107.14W	Sheriff/ Trout Creek	Earthfill/ Irrigation	1955/Local government	20/192	1.8	Rock slide	Right abutment	Right valley wall is huge Quaternary landslide mass, probably formed after glacier retreat. No problems.	Colton and others (1975d)/Colorado Division of Water Resources
United States/ Colorado/ 38.25N, 107.54W	Silver Jack/ East Fork Cimarron River	Earthfill/ Irrigation	1971/Federal government	53/320	18.9	Huge rock slide in valley wall	Right abutment	Excavations for right end of dam were made in toe of slide, causing 375,000-m^3 slide reactivation. Remedial measures: (1) resloping slide, (2) redesigning dam to avoid further cutting at toe of slide, (3) horizontal and surface drains, and (4) 87,000-m^3 buttress fill. Results were successful.	Logan and Davis (1972), Colton and others (1975g)/U.S. Bureau of Reclamation
United States/ Colorado/ 40.03N, 107.12W	Stillwater No. 1/Bear River	Earthfill/ Irrigation	1939/Private	27/457	9.1	Massive rock slides	Entire dam and reservoir	Massive Quaternary rock slides filled valley after glacier retreat. Dam built on toes of slides. No problems.	Colton and others (1975f)/Colorado Geological Survey

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Colorado/ 38.81N, 106.60W	Taylor Park/ Taylor River	Earthfill/ Irrigation, recreation	1937/Federal government	63/188	1.39	Thick talus cone	Right abutment	Right abutment covered by thick talus cone from sedimentary rock cliffs. Talus removed before construction except for area ~25 m downstream from centerline to downstream toe.	None/U.S. Bureau of Reclamation
United States/ Colorado/ 37.01N, 106.45W	Trujillo Meadows/ Los Piños River	Earthfill/ Recreation	1956/State government	15/50	1.6	Rock slide in tuffs and ash flows	Left abutment and foundation	Dam built on toe of large Quaternary rock slide that had blocked the river. No stability problems, but in 1990s seepage through left abutment became unacceptable. Impervious cutoff placed through left abutment in 1998.	Colton and others (1975a), Lipman (1975)/Colorado Division of Water Resources; U.S. Forest Service
United States/ Colorado/ 40.04N, 107.07W	Upper Stillwater/ Bear River	Earthfill/ Recreation, fish and wildlife	1965/State government	12/84	1.3	Slide in volcanic rock, shale, and glacial deposits	Entire dam on landslide and glacial deposits	Valley walls are covered by massive Quaternary landslides (mixtures of sandstone and shale from Browns Park and Morrison Fms.), Tertiary volcanics, and glacial deposits. At damsite, landslide and glacial deposits are intermingled. No dam problems related to geology.	Colton and others (1975f); Madole (1989)/Colorado Division of Water Resources; R. Madole (U.S. Geological Survey, oral commun., 2002)
United States/ Colorado/ 39.23N, 107.82W	Vega/ Plateau Creek	Rockfill and earthfill/ Irrigation	1959/Federal government	49/640	39.3	"Old landslide"	Right abutment	Much of right abutment area is part of large Quaternary landslide (Soule, 1986). In 1984, a small part reactivated, slightly damaging spillway. No current activity.	Colton and others (1975c), Soule (1986)/U.S. Bureau of Reclamation
United States/ Colorado/ 39.06N, 107.87W	Vela/Surface Creek tributary	Earthfill/ Irrigation	1959/Private	12/191	0.7	Massive rock slide	Entire dam and reservoir	Entire dam and reservoir are on Grand Mesa landslide complex (mainly basalt on claystone, mantled by glacial deposits). Minor foundation seepage. Local slide problems at spillway.	Yeend (1969, 1973), Colton and others (1975c), Baum and Odum (1996, 2003)/ Colorado Division of Water Resources

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Colorado/ 39.01N, 108.00W	Ward Creek/ Ward Creek	Earthfill/ Irrigation, recreation	1957/Private	14/384	0.7	Massive rock slide	Entire dam and reservoir	Entire dam and reservoir are on Grand Mesa landslide complex (mainly basalt on claystone, mantled by glacial deposits).	Yeend (1969, 1973), Colton and others (1975c), Baum and Odum (1996, 2003)/ Colorado Division of Water Resources
United States/ Colorado/ 40.33N, 106.52W	Whiteley Peak/ Diamond Creek	Earthfill/ Irrigation, water supply	1952/Private	19/236	1.6	Shale slide	Entire dam	Slides in Pierre Shale form both abutments and foundation of dam. Reactivation of part of right abutment slide in 1986 slightly damaged spillway. No other serious effects.	Hail (1968), Colton and others (1975f), Madole (1991a)/ Colorado Division of Water Resources; R. Madole (U.S. Geological Survey, oral commun., 2002)
United States/ Colorado/ 40.55N, 107.05W	Yamcolo/ Bear River	Earthfill/ Irrigation, water supply	1980/Local government	34/ 1,214	14.9	Rock slide and debris flow	Both abutments	Right end of dam on huge Quaternary rock slide; left end and part of left foundation on Quaternary debris flow. No problems.	Colton and others (1975f)/Colorado Geological Survey; Colorado Division of Water Resources
United States/ Colorado/ 39.04N, 107.91W	Young's Creek Nos. 1 and 2 (one dam)/ Young's Creek tributary	Earthfill/ Irrigation	1952/Private	17/154	1.0	Rock slide	Foundation and abutments	Entire dam and reservoir are on Grand Mesa landslide complex (mainly basalt on claystone, mantled by glacial deposits). Some seepage at both abutments. Left abutment has been grouted (with little success). Local blanketing with membranes tried without long-term success. Dam is stable.	Yeend (1969, 1973), Colton and others (1975c), Baum and Odum (1996, 2003)/ Colorado Division of Water Resources

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Colorado/ 39.19N, 107.89	YT Ranch/ Grove Creek	Earthfill/ Recreation, irrigation	1911/Private	12/274	0.3	"Old debris flow"	Entire dam and reservoir	Entire dam and reservoir are on "old debris flow" that originated on Grand Mesa (Soule, 1988). Dam is stable, but has considerable seepage through foundation.	Colton and others (1975c), Soule (1988)/Colorado Division of Water Resources
United States/ Idaho/ 43.36N, 115.44W	Anderson Ranch/South Fork Boise River	Earthfill-rockfill/Irrigation, hydroelectric	1971/Federal government	139/411	608	Rockfall (talus)	Right abutment	Before construction, right abutment was covered by thick layer of basalt talus, which was removed to granite bedrock under zone 1. Partially removed ("engineered") under upstream shell; left in place under downstream shell. New landslide has occurred into reservoir at upstream edge of "engineered" talus slope. Seepage on right valley wall downstream from dam apparently passes through talus.	None/U.S. Bureau of Reclamation
United States/ Idaho/ 43.33N, 111.21W	Palisades/ Snake River	Earthfill/ Irrigation, hydroelectric, flood control, recreation, fish and wildlife	1957/Federal government	82/640	1,800	Rock slide	Right abutment	Large slide at least 10,000 yr old. Maximum thickness ~70 m; width along upstream part of right abutment and shore ~1 km. Landslide material mainly andesite cobbles and boulders in matrix of silt, sand, gravel. Closely monitored; thus far, no movement. No problems.	Oriel and Moore (1985)/U.S. Bureau of Reclamation
United States/ Kansas/ 39.81N, 99.94W	Lovewell/ White Rock Creek	Earthfill/ Flood control, irrigation, recreation	1957/Federal government	28/ 2,590	230	Shale slides	Right abutment	Entire abutment slope above right end of dam poses threat to dam. In 1955, shale slide occurred during construction; 95,000 m^3 of slide material was removed. Abutment now buttressed by dam and two berms. However, minor sliding continues in abutment above dam. In 1985, instrumentation and monitoring were recommended.	None/U.S. Bureau of Reclamation

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Kentucky/ 36.96N, 84.27W	Laurel/ Laurel Creek	Rockfill/ Flood control, hydroelectric, recreation	1973/Federal government	86/433	537	Bedding-plane shears	Both abutments	Pre-existing bedding-plane displacement caused by stress relief in valley. Shear zones and fractures of foundation rock at damsite were filled with grout as part of grout curtain beneath core of dam.	Radbruch-Hall and Varnes (1976)/U.S. Army Corps of Engineers
United States/ Kentucky/ 38.00N, 85.32W	Taylorsville/ Salt River	Rockfill and earthfill/Flood control, recreation	1983/Federal government	49/390	360	Small pre-existing slide	Left abutment	Small pre-existing slide in sedimentary rocks at left end of dam. Occasional minor movement of rock in abutment immediately above end of dam; leads to need for minor maintenance. No other problems.	None/U.S. Army Corps of Engineers
United States/ Montana/ 49.59N, 114.28W	Bass Lake/ Bass Creek	Earthfill/ Irrigation	1952/Private	11/137	4.4	Rock fall (talus)	Left abutment	Downstream left shell of dam placed on talus slope. Remedial measure: sheetpiling for length of dam.	None/Montana Water Resources Division; consultant's report
United States/ Montana/ 47.20N, 113.72W	Black Lake/ Jocko River	Earthfill/ Irrigation	1967/Federal government	26/166	6.4	Rock slide and talus	Right abutment	Dam founded on ancient landslide dam. Considerable seepage through rock slide and talus. In 1992, 6 ha of 1.5-mm-thick polyethlylene membrane protected by geotextiles was installed in slide/talus. Abutment continues to leak. Downstream berm being considered.	None/U.S. Bureau of Reclamation; U.S. Bureau of Indian Affairs
United States/ Montana/ 46.65N, 111.73W	Canyon Ferry Dam/ Missouri River	Concrete gravity/ Hydroelectric, flood control, irrigation, water supply, recreation	1954/Federal government	69/328	2,529	Bedding-plane slip in shale	Left abutment	Several left-abutment bedding-plane slips in shale were excavated to competent bedrock. However, one prominent slip was only partially removed providing a short path for reservoir water to enter foundation. Remedial measure: two cutoff tunnels were placed parallel to dam axis and filled with concrete; they apparently were successful.	None/U.S. Bureau of Reclamation
United States/ Montana/ 45.49N, 110.98W	Hyalite (Middle Creek)/ Hyalite Creek	Earthfill/ Irrigation, water supply	1951/State government	38/580	15.8	Slide in glacial debris	Left abutment	Geotechnical consultant to State of Montana identified left abutment as being "founded on mixed landslide and glacial deposits composed of clay, silt, sand, poorly sorted gravel, rock fragments, conglomerate, and boulders." During 1990s, compacted earth liner placed to lower seepage rate. No stability problem.	None/Montana Water Resources Division; consultant's report

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Montana/ 48.83N, 113.52W	Lake Sherburne/Swiftcurrent Creek	Earthfill/ Irrigation	1921/Federal government	33/366	136.5	Slide in glacial deposits	Both abutments	Valley walls: massive landslide debris derived mainly from glacial deposits. Original foundation treatment included three continuous cutoff trenches reaching into till across valley bottom. Prior to 1960, movement of left abutment damaged original spillway; abutment remains unstable. Monitoring continues.	Lowe (1988), Carrara (1990), Whipple (1992)/ U.S. Bureau of Reclamation
United States/ Montana/ 46.56N, 113.31W	Lower Willow Creek/Lower Willow Creek	Earthfill/ Irrigation	1962/Local government	29/296	7.7	Rock fall (mainly talus)	Left abutment	Considerable seepage through lower left abutment. However, most seepage apparently is through jointed quartzite and argillite, not through the talus/colluvium.	None/U.S. Natural Resources Conservation Service
United States/ Montana/ 45.49N, 111.64W	Madison/ Madison River	Concrete gravity/Hydroelectric, flood control, water supply, recreation	1907/ Hydroelectric power company	12/78	52	Rock slides	Right abutment	Right abutment is in toe of pre-existing slide in metamorphic rock. Steel piles and concrete buttress used to anchor right abutment.	None/Site visit; C. Ruleman (oral commun., 2002)
United States/ Montana/ 45.54N, 110.92W	Mystic Lake/ Bozeman Creek	Earthfill/ Irrigation, water supply	1904/Private	13/119	1.5	Flow in volcanic breccia	Left abutment and left end of foundation	Flow of volcanic breccia dammed Bozeman Creek ~200 yr B.P. This landslide formed left abutment and left end of dam foundation. Dam was purposely breached in 1982 and 1985 because of leakage and risk to downstream population.	Roberts (1964), Hayes (1981), High County Independent Press (1985)/Reports: consultants; U.S. Army Corps of Engineers; U.S. Forest Service; Bozeman Creek Reservoir Association

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Montana/ 46.80N, 112.81W	Nevada Creek/ Nevada Creek	Earthfill/ Irrigation	1938/State government	32/330	21.3	Rock and earth slide	Both abutments; much of foundation	Material underlying much of dam and against which dam abuts at both ends is mass of irregular boulders of basalt in clay. Mass is ancient landslide that moved down valley slopes to stream channel. Foundation is stable, but there has been seepage at both abutments and under dam. Remedial measures: (1) toe berm and (2) seepage collection system using relief wells and shallow drains.	Sanders and others (2001)/U.S. Bureau of Reclamation; Montana Water Resources Division; consultants' reports
United States/ New Mexico/ 35.40N, 104.19W	Conchas/ Canadian River (Conchas River)	Concrete gravity-rockfill/ Irrigation, recreation, debris control	1940/Federal government	72/ 5,944	874	Open joints in sandstone and shale	Both abutments	Valley walls consist of jointed (often slickensided) sandstone and shale. As construction scaling progressed to stable rock, new joints opened. To prevent this, reinforced columns were used to act as beams for lateral support. Today, dam acts as its own buttress.	Stratton (1938), Crosby (1939)/None
United States/ New Mexico/ 36.88N, 105.28W	Costilla/ Costilla River	Earthfill/ Irrigation	1920/Private	42/238	37.5	Massive landslide	Right abutment	Right end of dam adjacent to toe of deep-seated ancient landslide in volcaniclastics, which originally were identified as glacial debris. In 1985, decision was made to rehabilitate dam because of embankment seepage. During reconstruction, reactivation (volume: 8–9 million m^3) of landslide occurred. Berm added for stability. Slide now stable.	Dunn and Haneberg (1998), Dunn (1999, 2000), Haneberg (1999)/U.S. Bureau of Reclamation; New Mexico State Engineer
United States/ New Mexico/ 36.59N, 106.75W	El Vado/ Chama River	Earthfill with steel-membrane face/ Irrigation, water supply, recreation	1935/Private conservancy district	70/404	258	Bedding-plane rock slide	Left abutment	Left abutment and canyon wall for about 1 km upstream and downstream are large, ancient (~10,000 yr B.P.) slide in sandstone and shale. Major grouting program in left abutment during construction. Within 3 years of reservoir filling, steel-plate membrane buckled, possibly due to abutment deformation. Repaired in 1955; stable since.	Sherard and others (1963, p. 481–482)/ U.S. Bureau of Reclamation

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ New York/ 42.15N, 79.01W	Site 19/ Battle Creek	Earthfill/ Flood control	1971/Local government	20/146	0.48	Slump in sedimentary rocks	Lower left abutment	Ancient slump in shale/siltstone was not recognized during construction. Because of dangerous seepage, dam was breached in 1980. Further exploration found slump underlain by alluvium. Dam was redesigned and rebuilt in 1981. Remedial measures installed: (1) cutoff trench deepened to bedrock, (2) cutoff trench into embankment, and (3) enlargement of foundation drainage system. Failure to recognize landslide in abutment resulted in substantial economic loss.	Kirkaldie and Thomas (1984), Agnew (1985), Kiersch and James (1991)/None
United States/ North Dakota/ 48.46N, 101.58W	Lake Darling/ Souris River	Earthfill/ Recreation, fish and wildlife	1936/Federal government	12/ 1,006	280	Slumps in clay till	Both abutments	Slumps in both valley walls (age: ~11,000 yr B.P.). No movement in past 10,000 yr. Toes of slumps removed by post-slide erosion along floor of Souris River valley. Slides cause no problems to dam.	Lemke (1960, p. 96, plate 12), Kehew (1983)/U.S. Bureau of Reclamation report; consultant's report
United States/ Oregon/ 42.42N, 122.78W	Agate/ Dry Creek	Rockfill and earthfill/ Irrigation, recreation	1966/Federal government	26/ 1,158	7.02	Shallow slump	Left abutment	Shallow landslide in volcanic rocks occurred at left abutment during construction; debris was removed and slope of excavation flattened. Slump moved again in early 1980s; toe was then excavated and rockfill placed as buttress. Dam is now stable.	Lockhart (1998)/ U.S. Bureau of Reclamation
United States/ Oregon/ 45.46N, 121.85W	Bull Run Lake/Bull Run River	Concrete gravity/ Water supply	1965/City government	17/46	17.9	Massive landslide (vol. ~110 million m³)	Entire dam on landslide	Dam constructed on prehistoric landslide dam about 70 m thick. Considerable seepage emerges from landslide dam material downstream of dam. About 60 percent of flow in Bull Run River downstream comes from these springs.	Schulz (1980), Snyder and Brownell (1996)/ City of Portland

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Oregon/ 45.50N, 122.10W	Bull Run No. 2/Bull Run River	Rockfill/ Hydroelectric, water supply	1962/City government	44/275	30.8	Rock slide: andesite and basalt over soft volcanics	Both abutments	Valley floor in basalt; both abutments are stationary slide debris consisting of andesite/basalt rubble in matrix of clay, silt, and sand. Following construction, occurrence of springs downstream from dam resulted in installation of extensive grout curtain. Some seepage continues.	Beaulieu (1974), Schulz (1980), Hammond and Griffiths (1998), Mohammadi and others (2000)/ U.S. Army Corps of Engineers; City of Portland
United States/ Oregon/ 44.24N, 118.78W	Canyon Creek Meadows/ Canyon Creek	Earthfill/ Recreation	1963/State government	18/53	0.49	Rock slide	Left abutment and part of right abutment	Left abutment and part of right abutment are remnants of large rhyolitic rock slide that formerly blocked stream channel. Seepage through left abutment. When visited in 1998, reservoir was empty and dam was not functioning.	Holdredge (1957)/Oregon Department of Water Resources; Oregon Department of Fish and Wildlife; U.S. Forest Service; U.S. Army Corps of Engineers
United States/ Oregon/ 45.52N, 122.71W	City of Portland Dam No. 3/Bull Run River	Concrete gravity/ Water supply	1894/City government	16/30	0.06	“Ancient” landslide in basalt and clay	Foundation and right abutment	Movement in “phenomenal landslide” (volume: ~2.6 million m^3) noted during construction (Clarke, 1904). From 1895–1903: drainage tunnels installed; 1904–76: reservoir linings rebuilt. In 1977, flexible membrane liner installed.	Clarke (1904)/ Oregon Department of Water Resources; consultants’ reports
United States/ Oregon/ 42.71N, 122.74W	Elk Creek/ Elk Creek	Roller-compacted concrete (RCC)/Flood control, irrigation	Environmental concerns halted construction in 1986/Federal government	Planned: 76/786	125	Rock slide (volcanic rocks)	Right abutment	During construction, three low-angle “shear zones” noted in right abutment. Excavation caused 7 cm of movement before concrete-filled key trench was installed to buttress sliding mass. Dam was half completed when project was terminated for environmental reasons (not because of slide problems).	Amundson and Scofield (1998)/ U.S. Army Corps of Engineers; consultant’s report

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province /latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Oregon/ 42.17N, 122.60W	Emigrant/ Emigrant Creek	Earthfill-rockfill, concrete/ Irrigation, recreation, flood control	1924/Federal government	62/229	57.6	Rock slide	Right abutment	Pre-existing slide in sandstone, siltstone, and shale reactivated during construction; minor movement since. Most of slide is on right shore immediately upstream from dam. Mass appears fairly stable at present; dam is in no danger.	Hammond and Griffiths (1998)/ U.S. Bureau of Reclamation
United States/ Oregon/ 45.09N, 122.05W	Frog Lake/ Oak Grove Fork, Clackamas River	Earthfill/ Hydroelectric	1955/Private power company	15/738	0.65	Huge ancient rock slide (area ~50 km^2)	Entire dam and reservoir	Seepage and cracking of reservoir bottom were a continuing maintenance problem for this dam. In 1991, it was recognized that Frog Lake Dam is located on the reactivated part of a 50-km^2 landslide (basalt and andesite rubble in tuff breccia). Dam was rebuilt in 1998.	Hammond (1999, Cornforth and Mikkelsen (2000)/ Federal Energy Regulatory Commission; U.S. Forest Service; Oregon Department of Water Resources; consultants' reports; company report
United States/ Oregon/ 42.13N, 122.47W	Keene Creek/ Keene Creek	Rock-faced earthfill/ Hydroelectric, irrigation	1959/Federal government	25/170	0.48	Rotational earth slump	Right abutment	Slump is chaotic mixture of weathered rock fragments, sand, silt, and clay. Slump recognized prior to construction, resulting in moving spillway from right to left end. Abutment is stable, but produces some seepage.	None/U.S. Bureau of Reclamation; consultants' reports
United States/ Oregon/ 45.08N, 121.96W	Lake Harriet/ Oak Grove Creek	Concrete arch buttressed with rockfill/ Hydroelectric	1923/Private power company	21/57	0.49	Edge of huge rock slide	Left abutment	Left abutment (basalt) is toe of huge landslide noted above for Frog Lake Dam. Slide has been moving toward dam, causing cracking of arch. Remedial measures installed in 1985: (1) impervious bentonitic membrane placed against upstream dam face by means of a tremie pipe and (2) rockfill buttresses against both dam faces.	Schroeder and others (1988)/Oregon Department of Water Resources; consultants' reports

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Oregon/ 43.91N, 122.75W	Lookout Point/Middle Fork Willamette River	Earthfill/ Flood control, irrigation, navigation, hydroelectric, recreation	1953/Federal government	84/462	589	Slides in volcanic tuff altered to clay; talus	Right abutment	Remnants of clay/talus deposit on both sides of valley. Right end of core trench was excavated through pre-existing large slide, resulting in reactivation upstream of trench. New slide deposit was removed, but pre-existing slide material downstream from core trench apparently remains in place and is stable.	Howell (1952), Staples (1964)/U.S. Army Corps of Engineers report
United States/ Oregon/ 44.30N, 120.73W	Ochoco/ Ochoco Creek	Earthfill (hydraulic fill)/ Irrigation	1920/Private irrigation district	38/411	57.3	Large rock slide–lateral spread	Right abutment	Late Pleistocene landslide forming right abutment probably was caused by plastic flow of bentonitic zones in dacitic tuff and claystone. Site was probably chosen because of landslide-caused valley constriction. Seepage through right abutment has been continuing problem. Modification during 1990s: deep interceptor trench with zone of impervious material reduces seepage.	Mumford (1994), Carter (1998a,b), Kunzer (1998)/U.S. Bureau of Reclamation
United States/ Oregon/ 44.72N, 121.25W	Pelton Regulating Dam/ Deschutes River	Concrete gravity/ Hydroelectric, flood control	1950/Private power company	12/325	4.32	Translational/ rotational rock slide in volcanic tuff	Left abutment	"The left abutment of the regulating dam was constructed on the toe of this extensive ancient landslide" (Benson and Pate, 1998). No problems.	Kent (1981), Benson and Pate (1998)/None
United States/ Oregon/ 45.95N, 123.92W	Peterson Point/South Fork Necanicum River	Earthfill/ Water supply	1954/Local government	14/79	0.21	Slides in mudstone	Both abutments	There has been no movement of abutment slides since construction. Dam was raised to 14-m height in 1996. No problems.	None/Oregon Department of Water Resources; consultants' reports

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Oregon/ 45.53N, 122.99W	Sams Valley/ Sams Creek, Zana Creek	Earthfill/ Irrigation	1956/Private irrigation district	19/101	1.48	Large rotational landslide	Right abutment	Low ridge at right abutment and right shore of reservoir apparently formed by large rotational landslide in sandstone. Seepage occurs through landslide mass. Stability and seepage satisfactory under reduced reservoir filling dictated by State of Oregon.	None/Oregon Department of Water Resources
United States/ Oregon/ 45.49N, 123.21W	Scoggins/ Scoggins Creek	Earthfill/ Irrigation, water supply	1975/Federal government	46/817	77.1	Earth slide	Right abutment	Quaternary landslide in sandy silt and silty sand forms right abutment. Monitoring program checks for movement every 3 years; there has been none.	None/U.S. Bureau of Reclamation; U.S. Geological Survey
United States/ Oregon/ 45.37N, 123.70W	Skookum Lake/Fawcett Creek	Earthfill/ Water supply	1965/Public utility	13/192	1.4	Debris slide in soil and rock	Right abutment and right 100 m of foundation	Dam was built on "old" (>500 yr B.P.) landslide dam. A deep (~7 m) core trench was excavated through landslide deposit to reduce seepage.	None/City of Tillamook reports; consultant's report; R. Lindquist (written commun., 1998)
United States/ Oregon/ 43.53N, 118.08W	Star Mountain/ Granite Creek	Earthfill/ Irrigation	1961/Private	21/87	1.8	Large slide in siltstone (tuff?) and basalt	Right abutment	Entire right bank of Granite Creek in vicinity of dam and reservoir is located on toe of huge ancient landslide. In 1983, original spillway (at right abutment) was eroded out by floodwater. Right end of dam rebuilt with circular concrete spillway passing through embankment.	Holton (1983)/ Oregon Department of Water Resources; consultants' reports
United States/ Pennsylvania/ 40.38N, 79.02W	Sugar Run/ Little Sugar Run Creek	Earthfill/ Water supply	1907/Water utility company	18/274	0.58	Rock slide	Right abutment	Prehistoric rock slide (sandstone, siltstone, and shale) forms right abutment. Dam has long history of foundation/abutment leakage. Flood in 1990s caused minor reactivation of right-abutment landslide.	None/Consultants' reports

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province /latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm^3)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ South Dakota/ 44.45N, 100.39W	Oahe/ Missouri River	Earthfill/ Flood control, hydroelectric, irrigation, navigation, recreation	1966/Federal government	75/ 2,835	29,000	Rotational slides in shale	Remnant of small slide in right abutment; construction slide in left abutment	Pre-existing slides in shale originally formed much of right abutment. Slide occurred in left abutment during construction; 5.0 million m^3 was removed (3.5 million m^3 used as buttress). Probably some remains beneath embankment. Part of small slide remains in right abutment. Both abutments are buttressed by weight of dam. No stability problems.	Crandell (1951, 1952, 1958, p. 72–77), Engineering Division (1958), Knight (1963)/ D.R. Crandell (U.S. Geological Survey, oral commun., 1997)
United States/ Texas/ 97.22N, 31.60W	Waco/ Bosque River	Earthfill/ Water supply, flood control	1965/Federal government	42/ 5,464	1,021	Basal slide in Pepper Shale	Foundation	Slide in Pepper Shale foundation occurred during construction (1961); embankment was 93 percent completed. Slide in embankment was a slump; translational in foundation shale. Length of slide: 500 m. Remedial measures: (1) embankment slopes extended at flatter slopes than original and (2) berm placed at lower toe.	Beene (1967), Stroman and others (1984)/ None
United States/ Utah/ 40.87N, 111.03W	Boyer Lake/ Chalk Creek	Earthfill/ Irrigation	1939/Private	14/396	0.01	Large landslide complex	Entire dam	Dam and reservoir entirely within large (~50 km^2) landslide area. No problems have been reported.	Bryant (1990)/ None
United States/ Utah/ 40.73N, 109.21W	Calder/ Pot Creek	Earthfill/ Irrigation	1989/State government	15/114	2.8	Block slide in Precambrian sandstone	Left abutment	Small sandstone and shale bedding-plane block slide noted before construction. Cement grout curtain added to successfully prevent seepage. Slide buttressed by dam.	Everitt and Schuster (1999)/Utah Division of Water Resources
United States/ Utah/ 40.72N, 109.17W	Crouse/Pot Creek	Earthfill/Recreation, fish and wildlife	1952/State government	11/306	1.34	Small block slide in sandstone/ shale	Left abutment	"Ancient" rock-block movement of sandstone blocks that form left abutment. Seepage problems occurred through the slide. Repairs were made while reservoir was drawn down. Reservoir was refilled in 1992.	Everitt and Schuster (1999)/Consultant's report; Utah Division of Water Resources

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Utah/ 39.62N, 110.39W	Grassy Trail/ Whitmore Canyon Creek	Earthfill/ Water supply	1952/Private	27/183	1.4	Earth-rock slumps in Cretaceous shale	Both abutments	Since construction, small slides have occurred in both abutments (but especially in the right) in unconsolidated materials derived from mudstone, shale, and sandstone. Greatest movement was in 1957 and 1969; only minor activity at present. Movement and seepage are monitored.	Everitt and Schuster (1999)/Utah Geological Survey; Utah Division of Water Resources; U.S. Geological Survey
United States/ Utah/ 39.29N, 111.27W	Joes Valley/ Seely Creek	Earthfill/ Irrigation, recreation, fish and wildlife, flood control	1966/Federal government	58/229	77	Slide in sandstone-shale colluvium and talus	Both abutments	Impervious cutoff to bedrock through about 10 m of colluvium/talus cover at both abutments. Part of colluvium/talus left in place and shaped on downstream parts of both abutments. Slide in talus of right abutment during construction. Earthquake-induced slide occurred in right-abutment talus in 1988; cracks remain in abutment area. Seepage in right-abutment slide area. Seepage collection pipes, collection wells, and seepage monitoring points have been installed.	None/U.S. Bureau of Reclamation reports
United States/ Utah/ 40.41N, 111.71W	Jordanelle/ Provo River	Earthfill/ Water supply	1993/Federal government	119/ 1,164	448	Rock-block slide in Tertiary volcanics	Left abutment	Andesite-porphyry rock-block slide (volume ~75,000 m³) found in left abutment during construction. Location of slide was centerline to downstream toe. Most was removed. "Dental work" assured stability during construction. Later, buttressing effect of dam provided stability.	Machette and others (1991), Dow (1995), Everitt and Schuster (1999)/ U.S. Bureau of Reclamation
United States/ Utah/ 40.91N, 109.87W	Long Park/ Sheep Creek	Earthfill/ Irrigation	1980/Private irrigation company	35/262	18.0	Bedding-plane creep in sandstone/ shale	Left abutment	Joints in sandstone/shale left abutment open as much as 0.75 m due to bedding-plane creep resulting from stress relief. Open joints were grouted (triple-line grout) during construction; however, seepage occurred through left abutment. In late 1990s, a 20-m-deep concrete cutoff wall was placed through the open-jointed rock to stop seepage.	Forrest and others (2001)/U.S. Natural Resources Conservation Service

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Utah/ 37.86N, 109.36W	Loyd's Lake/ South and Pole Creeks	Earthfill/ Irrigation	1984/Private	23/457	5.3	Slump in Cretaceous shale	Right abutment	Abutment is marginally stable. Berm serves as buttress. Blanket drain underneath. Piezometers installed.	Harty (1991), Everitt and Schuster (1999)/ Utah Division of Water Resources; consultants' reports
United States/ Utah/ 40.49N, 111.10W	Mill Hollow/ Mill Hollow Creek	Earthfill/ Recreation	1962/State government	13/69	0.50	Earthflow or compound slump	Right abutment	Toe of large "earthflow or compound slump" in Tertiary volcanics forms the right abutment. Apparently, this landslide at one time dammed the creek, which has since eroded a small canyon through the landslide dam. Mill Hollow Dam was built in this canyon. Landslide has caused no problems to dam.	Everitt and Schuster (1999)/ Utah Division of Water Resources
United States/ Utah/ 40.56N, 110.49W	Moon Lake/ Lake Fork River	Earthfill/ Irrigation	1938/Federal government	46/338	61.0	Block slide in Precambrian shale	Left abutment	Left end of dam rests on landslide block. Cutoff trench was dug though block into in-place shale. Disturbed shale heavily grouted. Dam is stable.	Harty (1991), Everitt and Schuster (1999)/ U.S. Bureau of Reclamation
United States/ Utah/ 41.90N, 111.98W	Newton/ Clarkston Creek	Earthfill/ Irrigation	1946/Federal government	32/ 1,018	6.9	Deep-seated earth slide	Left abutment	Abutment is in earth-slide material derived from upslope shale. No serious problems.	Harty (1991), Everitt and Schuster (1999), Solomon (1999)/ None
United States/ Utah/ 37.66N, 109.44W	Recapture/ Recapture Creek	Earthfill/ Irrigation	1984/Private	43/884	19.7	Small slump in Jurassic shale	Both abutments	Abutments were formed of ancient, opposing landslides that were noted prior to construction. During construction of cutoff, left-abutment slide was reactivated. Cutoff extends to bedrock under center core of dam, leaving slide remnants under upstream and downstream parts of dam.	Montgomery (1980), Everitt (1993), Everitt and Schuster (1999)/Utah Division of Water Resources; consultant's report
United States/ Utah/ 37.87N, 112.68W	Red Creek/ Red Creek	Earthfill/ Irrigation	1980/Private	23/259	23.4	Large earth slide in Tertiary volcanics	Left abutment	Left abutment and reservoir shore underlain by large Holocene/late Pleistocene slide (thickness: ~60 m), mainly weathered volcanics. Dam buttresses toe of slide. No problems.	Everitt and Schuster (1999)/Utah Division of Water Resources

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Utah/ 40.76N, 111.10W	Smith and Morehouse/ Smith and Morehouse Creek	Earthfill/ Irrigation	1987/Private irrigation district	25/670	12.4	Valley-wide debris avalanche	Foundation, both abutments	Large avalanche (age ~4,000 yr B.P.) in sedimentary rock and glacial debris filled canyon to depth of 60 m. Dam built on debris, but key placed through the mass both for strength and imperviousness. No problems.	Harty (1991), Everitt and Schuster (1999)/ Utah Division of Water Resources
United States/ Utah/ 37.14N, 112.90W	South Creek/ South Creek	Earthfill/ Irrigation	1988/Private	21/226	2.2	Large slump in Triassic shale	Right abutment	Right abutment is slump block of sandstone, siltstone, and shale. Small slide shortly after reservoir filling. Remedial measures: (1) collection-drain system, (2) impervious seepage blanket, and (3) horizontal drains.	Harty (1991), Everitt and Schuster (1999)/ Utah Division of Water Resources; consultants' reports
United States/ Utah/ 37.76N, 112.77W	Yankee Meadows/ Bowery Creek	Earthfill/ Irrigation	1926/Private	10/137	1.27	Large slide in Tertiary volcanics	Right abutment	Dam is on toe of very large slide (gravitational or tectonic) from valley wall. Slide has had no negative effect on dam performance.	Everitt and Schuster (1999)/Utah Division of Water Resources
United States/ Vermont/ 44.38N, 72.77W	Waterbury/ Little River	Earthfill/ Flood control, recreation, hydroelectric	1938/State government	57/649	98.4	Rock fall	Foundation	Part of foundation located in narrow bedrock gorge. "Detached rock slabs along the right (west) side of the gorge form a roof over a piping tunnel known to have been a piping path in the past, and capable of being a piping path in the future if injected filter materials are destabilized" (Saber and others, 2001). Grouting program to prevent seepage was completed in 1985. Apparently, some seepage continues.	Saber and others (2001)/U.S. Army Corps of Engineers; Vermont Department of Environmental Conservation
United States/ Washington/ 45.64N, 121.93W	Bonneville/ Columbia River	Concrete gravity/ Hydroelectric, navigation, recreation	1937/Federal government	60/755	710	Large prehistoric landslide	Right abutment	Right abutment is toe of huge Bonneville landslide (age ~400 yr B.P.). Minor surficial movement currently occurring locally on the slide, but not at abutment location. Toe of slide is large and stable. No problems. Note: south end of the dam (navigation locks) also is on a pre-existing landslide (smaller than the Bonneville slide). Local problems during construction, but none at present.	Palmer (1977), Sager (1989), Keech and Sanford (1998)/U.S. Army Corps of Engineers.

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Washington/ 46.87N, 121.30W	Bumping Lake/ Bumping River	Earthfill/ Irrigation	1910/Federal government	19/892	46.5	Volcanic debris flow (lahar)	Entire foundaion	Dam was unknowingly built on a 1–2-m-thick lahar (age ~500 yr B.P.) from Mount Rainier. Considerable seepage through foundation. In 1990s, drainage trench and stability berm were constructed at downstream toe of dam.	None/U.S. Bureau of Reclamation
United States/ Washington/ 48.00N, 123.62W	Glines Canyon/ Elwha River	Left wing wall: earthfill/ Hydroelectric	1927/Private	Wing-wall height: 10–15 m	49.3	Rock/soil slide	Left end of wingwall	Field visit confirmed that left end of earthfill left wingwall (or saddle dam) of this 59-m-high concrete arch dam abuts a surficial rock/soil slide. No problems.	None/K.G. Neal (written commun., 2001)
United States/ Washington/ 47.96N, 118.98W	Grand Coulee/ Columbia River	Concrete gravity/Irrigation, hydroelectric, flood control	1942/Federal government	168/ 1,729	11,780	Soil slide	Right abutment	Varved clay at right abutment moved during construction. Stabilized by (1) building timber-crib retaining wall, (2) flattening the slope, and (3) freezing the soil above the wall. This soil-slide area was removed in 1967–81 when dam was lengthened to accommodate third powerplant.	Gordon (1937), Irwin (1938)/U.S. Bureau of Reclamation
United States/ Washington/ 47.27N, 121.79W	Howard A. Hanson/ Green River	Rockfill and earthfill/Flood control	1962/Federal government	72/152	169	Large landslide (area: >400 m × 600 m)	Right abutment	Gorge of Green River was cut into toe of a massive Pleistocene slide. Right end of dam is built on landslide deposits consisting of rock blocks up to 6 m in diameter and finer debris. Considerable seepage through right abutment. Remedial measures: (1) gravel drainage blanket, (2) horizontal drains, (3) drainage adit, and (4) relief wells.	Galster (1989a), Tabor and others (2000)/U.S. Army Corps of Engineers; Washington Division of Geology and Earth Resources
United States/ Washington/ 47.14N, 121.93W	Mud Mountain/ White River	Earthfill/ Flood control	1948/Federal government	130/213	131	Volcanic debris flow (lahar)	Both abutments	At both banks, dam abuts into Pleistocene lahar (originally thought to be glacial till). Concrete cutoff wall installed in 1989–90 through embankment and into rock foundation to control seepage.	Galster, R.W. (1989b), Graybeal (1991), Eckerlin (1992, 1993)/None

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Washington/ 47.94N, 119.02W	North (Banks Lake)/Upper Grand Coulee River	Rockfill and earthfill/ Flood control, navigation, irrigation, hydroelectric	1951/Federal government	44/442	1,572	Rotated slide block	Left abutment	Left abutment is a rotated slide-block segment of a basalt flow resting on slide-disturbed soft sediments. The left two-thirds of the dam rests on these slide-disturbed sediments. Cutoff trench was excavated through these materials. No operational problems.	Neff (1989), Gulick and Korosec (1990), Stoffel and others (1991)/U.S. Bureau of Reclamation
United States/ Washington/ 46.36N, 122.55W	SRS (Sediment retention structure)/North Fork Toutle River	Earthfill/ Debris retention	1988/Federal government	73/549	197	Debris flow	Entire dam	Dam was built on at least 30 m of debris-flow deposits from prehistoric eruptions of Mount St. Helens. Purpose is to retain sediment derived from the 1980 Mount St. Helens debris avalanche. In wet winters of 1996–97, dam retained 23 million m^3 of sediment.	Schuster (1989), Bernton (2000)/ U.S. Army Corps of Engineers
United States/ Washington/ 47.31N, 120.31W	Stemilt Main Dam/Orr Creek–off-stream	Earthfill/ Irrigation	1962/Private irrigation district	20/305	0.72	Massive landslide	Entire dam and reservoir	Entire dam and reservoir built on series of massive landslides (basalt over clay shale) collectively about 17 km long by 5 km wide. Reservoir leaked considerably through landslide material until impervious geosynthetic membrane was successfully placed in 1986.	Tabor and others (1982), Stoffel and others (1991)/ Washington State Department of Ecology
United States/ Washington/ 46.08N, 122.21W	Swift/ Lewis River	Earthfill/ Hydroelectric, flood control, recreation	1958/Private power company	126/640	931	Volcanic debris flow	Foundation and right abutment	Right abutment and channel bottom consist of thick, well-consolidated volcanic debris flow from prehistoric eruption of Mount St. Helens. In the channel, an open-cut excavation for cutoff was made to a depth of about 30 m; sheet piling driven from bottom of trench to bedrock (~25 m). Dam was built on lahar in right abutment. Drainage gallery to intercept any seepage. No apparent problems.	de Luccia (1958), Jensen (1981), Tilford and Sullivan (1981), Lowe (1988), Major and Scott (1988), Bliton (1989)/N.R. Tilford (oral commun., 1996)

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued*.

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ Washington/ 47.28N, 120.36W	Upper Wheeler/ Orr Creek	Earthfill/ Irrigation, recreation	1922/Private irrigation company	20/274	0.74	Massive landslide	Entire dam and reservoir	Entire dam and reservoir built on series of massive landslides (basalt over clay shale) collectively about 17 km long by 5 km wide. Minor leakage at left abutment has been controlled by installation of drains.	Tabor and others (1982), Stoffel and others (1991)/ Washington State Department of Ecology
United States/ Washington/ 46.81N, 120.67W	Wenas/ Wenas Creek	Rockfill and earthfill/ Irrigation, recreation	1911/Private irrigation district	27/160	6.78	Ancient large landslides	Both abutments	Both abutments are on ancient (probably pre-Pleistocene) landslides. Left abutment: steeply dipping sediments on basalt (neither in place). Right abutment: lower part of very large landslide mass. Both masses are so large that they are inherently stable. No problems.	Swanson and others (1979), Walsh and others (1987)/ Washington Division of Geology and Earth Resources
United States/ Washington/ 45.98N, 122.35W	Yale/ Lewis River	Earthfill/ Hydroelectric, flood control, recreation, fish and wildlife	1953/Private power company	98/457	496	Volcanic debris flow (lahar)	Both abutments and possibly the foundation	Right abutment: during construction, large basalt block moved. Partially removed by blasting; now stabilized by dam. Left abutment: slump in clayey tuff was removed; joints and “faults” then developed in overlying basalt. Stabilized by dam. Tilford and Sullivan (1981) showed lahar in channel at damsite; apparently, it was removed under the impervious part of the dam foundation. Not clear if lahar remains under outer shell. No problems.	Tilford and Sullivan (1981), Major and Scott (1988), Bliton (1989)/N.R. Tilford (oral commun., 1997)
United States/ Washington/ 45.98N, 122.35W	Yale Saddle Dam/Lewis River	Earthfill/ Hydroelectric, flood control, recreation, fish and wildlife	1953/Private power company	12/488	496	Volcanic debris flow (lahar)	Entire dam	Entire saddle dam is founded on volcanic debris flow (lahar). No problems.	Tilford and Sullivan (1981), Bliton (1989)/N.R. Tilford (oral commun., 1997)

Appendix table A. Dam characteristics, relation to landslides, mitigative measures, and cited references—*Continued.*

Country/ state or province/ latitude, longitude	Dam/river or stream	Dam type/ purpose	Year constructed/ owner	Height/ length (m)	Storage volume (Mm³)	Landslide type	Landslide position relative to dam	Comments	References/ sources of information
United States/ West Virginia/ 39.37N, 81.27W	McElroy's Run/ McElroy's Run Creek	Fly-ash embankment/ Fly-ash storage	1978/Public utility	74/655	24.53	Slide in colluvium	Left abutment	Before placing fly-ash embankment on downstream edge of tailings dam, slide was noted in colluvium of left abutment. Removal of unstable material not feasible. Remediation: grid of auger-cast grout columns was placed through unstable material.	Newman and others (2000)/ None
United States/ Wyoming/ 41.03N, 110.58W	Meeks Cabin/ Black Fork River	Earthfill/ Irrigation	1971/Federal government	59/964	47	Rock slide in shale	Right abutment	Ancient massive (area ~1 x 0.75 km) shale slide forms right valley wall. Dam constructed with deep cutoff trench. No landslide-related stability or seepage problems. However, seepage has occurred through glacial outwash materials in left abutment, resulting in 1994 construction of cutoff wall.	Gagliardi and Routh (1993)/ U.S. Bureau of Reclamation; Geological Survey of Wyoming

Schuster—**Interaction of Dams and Landslides—Case Studies and Mitigation**—Professional Paper 1723

ISBN 141131166-3

9 781411 311664